PROCEEDINGS

THE INSTITUTION OF CIVIL ENGINEERS

PART I
MAY 1954

ORDINARY MEETING

15 December, 1953

WILFRID PHILIP SHEPHERD-BARRON, M.C., T.D.,
President, in the Chair

The Council reported that they had recently transferred to the class of

Members

COTTAM, GEORGE BARNABY.
FIELD, WALTER TREMAYNE, B.Sc. (*Cape Town*).
PATERSON, WILLIAM.

and had admitted as

Graduates

ACHESON, MICHAEL ALEXANDER, B.Sc. (*Cape Town*).
ADAMSON, WILLIAM SCOTLAND, B.Sc. (*St. Andrews*).
ASKEW, THOMAS GODFREY, B.Sc. (*Durham*), Stud.I.C.E.
BADENOCH, GEORGE STUART GILCHRIST, Stud.I.C.E.
BAGNALL, JOHN BURFITT.
BAILEY, BRIAN WILLIAM, B.Sc.(Eng.) (*London*), Stud.I.C.E.
BEATTY, DESMOND WILLIAM, B.E. (*New Zealand*), Stud.I.C.E.
BROMLEY, RONALD FRANK SMITH, Stud. I.C.E.
CALDWELL, FRANK MICHAEL KINSON, B.Sc. (*Manchester*).
CASTLE, ROY KENNETH, B.Sc.(Eng.) (*London*), Stud.I.C.E.
CHODZKO-ZAJKO, WITOLD JOZEF, Stud. I.C.E.
COOKE, ROY STANLEY, B.Sc.(Eng.) (*London*).
COPELAND, BERTRAM GERALD THORPE, B.Sc. (*Durham*), Stud.I.C.E.
CREASY, DONALD EDWARD, B.A. (*Cantab.*).
DAVIES, PETER HOWELL, Stud.I.C.E.
DAVIES, THOMAS GLYNN, B.Sc. (*Wales*).
DEACON, JOHN ROBERT, Stud.I.C.E.
DEVINE, DESMOND HYLTON, B.Sc. (*Cape Town*).
DICKENS, WILLIAM RICHMOND, B.Sc. (Eng.) (*London*), Stud.I.C.E.
DIXON, ALAN JAMES BURNEY, B.Sc. (*Manchester*), Stud.I.C.E.
DRAYSON, JOHN ARTHUR.
EDE, NEVILLE BRUCE, Stud.I.C.E.
EDWARDS, CHRISTOPHER BRIAN, Stud. I.C.E.
EGAN, BRIAN STAVELEY, B.Sc. (*Leeds*), Stud.I.C.E.
ELLIOTT, JOSEPH EDWIN, B.Sc. (*Durham*).
EL MULA, MUKHTAR MOHAMMED FADL, Stud.I.C.E.

Englert, Alan Brown, B.Eng. (*Sheffield*), Stud.I.C.E.
Esler, Robert Acheson, B.Sc. (*Belfast*), Stud.I.C.E.
Evans, David Gerald, B.Sc. (*Wales*).
Fairbairn, Derek Sidney, B.Sc.(Eng.) (*London*), Stud.I.C.E.
Fam, Michael Yue-Onn, B.E. (*W. Australia*).
Finnimore, Hugh Martin, Stud.I.C.E.
Fisher, Jocelyn Cyril Frederick, Stud.I.C.E.
Galloway, John Hampden Hardie, B.Sc. (*Glasgow*), Stud.I.C.E.
Gaulton, Arthur Douglas, B.E. (*Sydney*).
Gillibrand, William, B.Eng. (*Liverpool*).
Goodwin, Alec Francis, B.Sc. (*Nottingham*).
Hancock, William Albert, Stud.I.C.E.
Havelock, John Henry William, B.Sc. (Eng.) (*London*), Stud.I.C.E.
Heath, Leslie William Albert.
Henderson, Richard John Alistair, B.Sc. (*Edinburgh*), Stud.I.C.E.
Hill, Reginald John, Stud.I.C.E.
Holland, Ronald Wilber, M.A. (*Cantab.*), Stud.I.C.E.
How, Robin Ridgeway, Stud.I.C.E.
Hutchison, John Forsyth, Stud.I.C.E.
Jackson, John Keith, B.Sc.Tech. (*Manchester*), Stud.I.C.E.
Johnstone, John Michael Charles, B.Sc.(Eng.) (*London*).
Jones, Robin Bethune, B.E. (*Tasmania*).
Julian, Ronald, B.Sc.(Eng.) (*London*), Stud.I.C.E.
Knill, Stanley Francis, B.Sc. (*Wales*).
Leitch, Robert John Stuart, B.Sc. (*Glasgow*), Stud.I.C.E.
Linn, John McAllister, Stud.I.C.E.
Lloyd, George Francis, B.Sc.(Eng.) (*London*), Stud.I.C.E.
Lomax, John Michael, B.Sc. (*Wales*), Stud.I.C.E.
Longman, Albert Denis, B.Sc.(Eng.) (*London*), Stud.I.C.E.
Loraine, Robert Kinlayside, B.Sc. (*Glasgow*), Stud.I.C.E.
McAll, David, B.Sc. (*Durham*).
McCormack, James Joseph, B.E. (*National*).
McGrath, Francis Henry, B.E. (*National*).
McIlroy, Peter Kirkpatrick, B.Sc. (Eng.) (*London*), Stud.I.C.E.
Mackay, David Steuart, B.Sc.(Eng.) (*London*).
McLeod, Stuart Wilson, B.Sc. (*St. Andrews*), Stud.I.C.E.
McMurray, Ronald Dickson, B.Sc. (*Wales*), Stud.I.C.E.
Martin, Peter Francis, B.Sc.(Eng.) (*London*), Stud.I.C.E.
Mellish, Allan Raymond, B.Sc. (*Cape Town*), B.A. (*Oxon.*), Stud.I.C.E.
Middleditch, Brian George, B.Sc. (*Nottingham*).
Millar, James Bruce, B.Sc. (*Belfast*), Stud.I.C.E.
Miller, Harold Wilfred, Stud.I.C.E.
Millgate, Leonard John, B.Sc.(Eng.) (*London*).
Mitchell, David Biggart, Stud.I.C.E.
Moakes, Willis, B.Eng. (*Liverpool*), Stud.I.C.E.
Moore, Bernard George, Stud.I.C.E.
Mottershead, Geoffrey, B.Sc.Tech. (*Manchester*), Stud.I.C.E.
Pearson, Thomas Gordon, B.Eng. (*Liverpool*).
Peverett, Leslie Maxwell, B.Sc. (Eng.) (*London*), Stud.I.C.E.
Porter, Maurice Garfield, B.Eng. (*Sheffield*), Stud.I.C.E.
Pyves, Peter Grant, B.A. (*Cantab.*), Stud.I.C.E.
Rich, David Blake, Stud.I.C.E.
Riordan, Peter Joseph, B.E. (*National*).
Robinson, Douglas, B.Sc. (*Durham*).
Roe, David Edgar, B.Sc.(Eng.) (*London*), Stud.I.C.E.
Rogers, John Michael Fortnum, B.Sc. (Eng.) (*London*), Stud.I.C.E.
Rogers, Kenneth, B.Sc. (*Bristol*), Stud. I.C.E.
Ross-Smith, Angus John, B.Sc. (*St. Andrews*), Stud.I.C.E.
Scarlett, John Hall, B.Sc.(Eng.) (*London*), Stud.I.C.E.
Seddon, Philip Anthony, B.Sc.Tech. (*Manchester*), Stud.I.C.E.
Selby, John Raymond, B.Sc.(Eng.) (*London*).
Sharp, Brian Downs, B.Sc.(Eng.) (*London*).
Shaw, John Beaumont, B.Sc. (*Bristol*), Stud.I.C.E.
Sherratt, Frank, B.Sc.(Eng.) (*London*), Stud.I.C.E.
Siebert, Colin John, B.Sc.(Eng.) (*London*), Stud.I.C.E.
Simmonds, Derek Tapson, B.Sc.(Eng.) (*London*), Stud.I.C.E.
Sleeman, Basil Hugh, Stud.I.C.E.
Smith, Alan, B.Sc. (*Durham*), Stud. I.C.E.
Smith, David, B.Sc.(Eng.) (*London*).
Smith, David Langstreth, B.Sc.(Eng.) (*London*).
Stainsby, Stanley John, B.Sc. (*Durham*), Stud.I.C.E.

Stewart, John, B.Sc. (*Glasgow*), Stud. I.C.E.
Sutherland, Andrew, B.Sc. (*Glasgow*).
Sutton, John Lewis Edward, B.A. (*Oxon.*), Stud.I.C.E.
Tidy, Anthony Brian Stafford, B.Sc. (*Birmingham*), Stud.I.C.E.
Wallace, William John, B.Sc.(Eng.) (*London*), Stud.I.C.E.
Wearne, Stephen Hugh, B.Sc.(Eng.) (*London*).
Whelan, Michael Noel, B.Eng. (*Liverpool*), Stud.I.C.E.
White, Donald Neale, B.Sc. (*Birmingham*), Stud.I.C.E.
White, James Bernard, B.Sc.Tech. (*Manchester*), Stud.I.C.E.
Whitelaw, Robert Stanley, B.Sc. (*Glasgow*), Stud.I.C.E.
Whitworth, Andrew Allen, M.A. (*Oxon.*), Stud.I.C.E.
Wijesinghe, Vitarana Aratchige Don Mahanil, Stud.I.C.E.
Williams, Michael Alwyn, B.Sc.(Eng.) (*London*).
Wray, Robert Christopher, B.Sc. (*Bristol*), Stud.I.C.E.
Young, Alexander Robert, B.Sc. (*Edinburgh*), Stud.I.C.E.

and had admitted as

Students

Akelewold, Kebede.
Akers, Douglas.
Alexander, Brian.
Allen, Reginald William.
Allester, Alistair Robert.
Bacon, George Albert.
Baker, John Trevor.
Ball, Frederick Joe.
Barton, Daniel Frederick.
Beckwith, Peter.
Bispham, Richard Anthony.
Bonham, Alan John.
Brian-Boys, Keith Charles.
Brokenshire, Colin Allen.
Brook, Jeremy David.
Bros, Peter Michael.
Brown, Thomas William Hill.
Burchess, David Sydney.
Bushell, Alan John.
Centa, Antony Richard.
Chamberlain, Benjamin Barry.
Chisholm, Ronald Arthur.
Cox, Graham Clive.
Cumming, Stanley.
Cunliffe, Michael Lister.
Debidin, Frederick.
Dixon, Paul Antony.
Duncan, Stewart Douglas.
Evans, John David.
Faluyi, Benjamin Ayodele Owen.
Fritzøe, Karl-Johan.
Gibbons, Michael Eddevane.
Goodwin, Geoffrey Rew.
Goulis, Dimitri.
Harvatt, Terence Keith.
Henderson, John Robert.
Hughes, Alan Osborne.
Ingram, John.
Jacob, Martin Benjamin.
Jarrett, Peter John David.
Kain, Vishva Mitra, B.Sc. (*Delhi*).
Kaye, John Cooper.
Kelly, Denis Paul.
Kulesza, Ryszard.
Kuruppu, Upali Srimath.
Lanyon, Claude John Edwin.
Larkin, Richard Neville.
Longlands, Henry Geoffrey, B.Sc. (*Nottingham*).
McNally Donal Neale.
Mannell, Raymond John.
Marriott, Keith Howard.
Marsh, John Vernon.
Martin, Kenneth Vernon.
Matharu, Sarjit Singh.
May, Michael John.
Michael, David James Blackwood.
Mitchell, Cecil Robert.
Mitchell, Donald Frederick.
Munden, Ronald William.
Nelder, John Edward.
Nutland, John Henry Douglas.
Nutt, Edward Daniel.
Oldham, Philip Howard.
O'Neill, Reuben William.
Osborne, Henry Robin.
Padbury, Robert Iain.
Patel, Shirish Bhailal.
Patton, John.
Pierce, Michael John.
Prior, Michael Arthur.
Ramsay, Cassels Alan Wilson.
Read, Colin.
Read, John.
Richardson, John Keith.
Rickett, James Ian.
Robertson, John Pearson.
Rome, George.
Rowe, Leslie John, B.Sc. (*Leeds*).
Rutherford, David.
Scriven, Ronald William.
Seymour, Michael William.
Shah, Harikrishna Ranchhodlal.
Sharples, Peter Desmond.

Sheppard, William John.
Singh, Matharu Mohan.
Smith, Ian Frederick.
Smith, Trevor John.
Smurthwaite, William.
Staniforth, Trevor.
Taylor, Ernest Hoodless.
Thompson, George Hunter.
Thurlow, Brian Bellew.
Toynbee, Philip Michael.
Visvesvaraya, Hosagrahar Chandrasekharaiya, B.E. (*Mysore*)
Watkinson, Graham.
Wharton, William.
Wijayasinghe, Don Maithriepala Seneviratne.
Williams, Alan.
Williams, John Hugh Hammerton.
Yates, Mark Archibald.

The following Paper was presented for discussion and, on the notice of the President, the thanks of the Institution were accorded to the Authors.

Paper No. 5983

"The Pimlico District Heating Undertaking"

by

Bryan Donkin, B.A., M.I.E.E.,
Abraham Elia Margolis, Dipl. Ing., and
Charles George Carrothers, B.Eng., M.I.Mech.E., M.I.E.E.

SYNOPSIS

The object of the Paper is to describe the Pimlico Scheme and to discuss the results of its first two years' operation against the background of the general subject of district heating with combined heat-electric generation. It is explained how the heat is generated by means of back-pressure turbines installed at Battersea power station and how the heat and electricity loads are balanced. Details are given of the method used for transmitting the heat across the River Thames from Battersea power station for distribution at the Pimlico Housing Estate. The design and operation of the heat accumulator are described and it is shown that the use of the accumulator is essential for the efficiency of heat-electric generation. The Paper concludes with a review of the possible future developments of combined heat-electric generation for the improvement of the hygienic conditions and the amenities of towns and cities.

Introduction

The Pimlico Housing Estate is an important part of the post-war reconstruction scheme planned, and already partly completed, by the Council of the City of Westminister. On the completion of the scheme now projected, the Pimlico District Heating Undertaking will supply about 3,200 dwellings with a population of about 11,000. The Estate was opened by Her Grace the Duchess of Marlborough at a ceremony on the 24th July, 1951, when it was formally named "Churchill Gardens." It was then in partial occupation and the District Heating Undertaking, which had formed an integral part of the scheme from the design stage onwards, was already supplying heat for space heating and hot tap-water to the residents. The Westminster City Council has already extended the District Heating Undertaking to a large block of flats in the vicinity, known as Dolphin Square, and arrangements have also been made to extend the supply of heat to the Council's Abbot Manor housing estate now in course of erection.

The heat utilized by the District Heating Undertaking is derived from

the exhaust steam of two of the turbo-alternators, which generate part of the auxiliary power at the Battersea power station of the British Electricity Authority. These machines have been installed by the Authority specially for the supply of heat to the Pimlico District Heating Undertaking and are designed to operate without any means of heat rejection to condensers cooled by circulating water from the Thames.

The heat supplied to the Undertaking is metered at Battersea for purchase by the Westminster City Council in the form of hot water heated by the exhaust steam. The hot water is transmitted to a substation at the housing estate by means of pipes laid in an existing Metropolitan Water Board tunnel under the Thames and distributed from that point by a network of pipes laid in ducts in the ground and in the basements of the buildings.

An important feature of the combined heat-electric scheme at Pimlico is the provision of a heat accumulator. This has several functions, the most important of which is to allow the back-pressure turbines to be worked independently of the demand for heat. It is shown in the Paper that the provision of this facility is essential to the economy of combined heat-electric generation.

The methods of supplying, distributing, and utilizing heat adopted by the City of Westminster for the Pimlico District Heating Undertaking are in accordance with the advice given by the late Mr S. B. Donkin, whom the Council appointed as their Consultant. Mr Donkin's interest in combined generation of heat and electricity and in district heating goes back many years, and on the 10th December, 1935, he presented a Paper[1] on the subject to the Institution.

At the request of the Institution, Mr A. E. Margolis, a co-Author of this Paper, submitted a memorandum[2] on District Heating for the Institution's post-war Reconstruction Committee in May 1941.

General Description

The Situation and Extent of the Housing Estate

The Churchill Gardens housing estate occupies an area of about 33 acres on the north bank of the Thames in the position shown on the small sketch map (*Fig. 1*). The development of the estate is planned in four sections indicated on Fig. 2, Plate 1, and the size and number of the flats in the various sections are shown in Table 1. A general view of the estate from the opposite side of the river is shown in *Fig. 3* (facing p. 262).

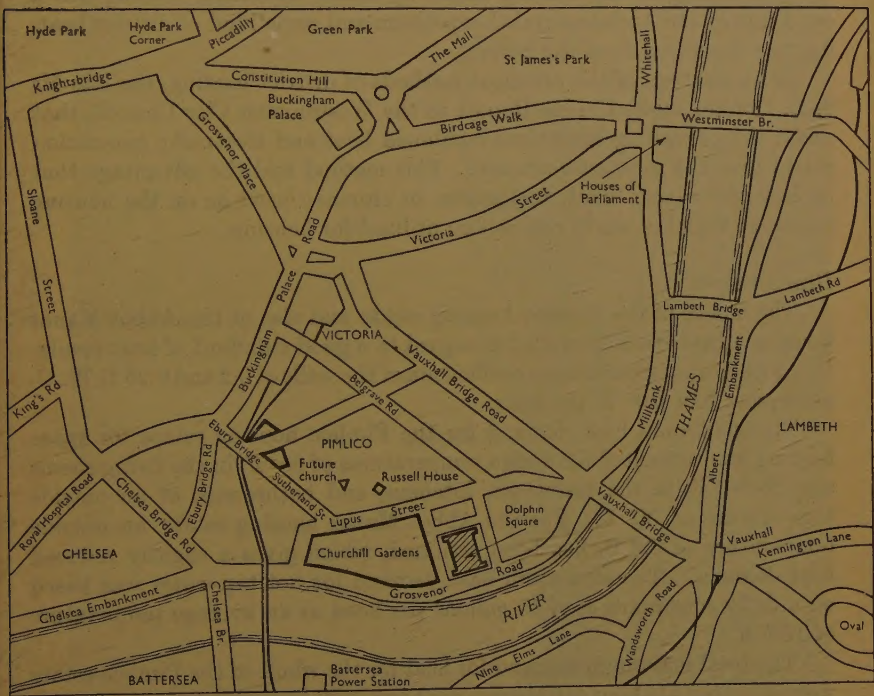
The majority of the flats are in eight- to eleven-storey blocks, but there are a number of three- and four-storey blocks; the estate also contains some maisonettes.

[1] The references are given on p. 285.

TABLE 1.—SIZE AND NUMBER OF FLATS

Section	Bed-sitting	Two rooms	Three rooms	Four rooms	Five rooms	Total
I	14	36	160	269	16	495
II	52	29	420	42	28	571
III	48	18	206	90	6	368
IV	1	18	78	104	8	209
Total	115	101	864	505	58	1,643

Fig. 1



KEY PLAN OF DISTRICT
(Approximate scale: 2·2 inches = 1 mile)

The housing scheme was designed by the Architects, Messrs Powell & Moya, and was the successful entry in an architectural competition. It has been described recently.[3, 4] It is sufficient to point out here that a high standard of convenience and comfort has been the aim. The services of space heating and hot water offered by the district-heating scheme forms a natural part of the general amenities of the estate.

Developments beyond Churchill Gardens

As shown in Fig. 2, Plate 1, the district-heating scheme has been extended beyond Churchill Gardens. A connexion, which has already been in operation for 2 years, has been made to provide heating services to the large block of service flats known as Dolphin Square situated immediately to the east of the estate. A further extension is now being made to the new Abbot Manor housing estate which is being built to the north-west of Churchill Gardens. On completion of the above extensions, about 3,200 flats with a population of about 11,000 will be served by the Pimlico District Heating Undertaking.

Method of District Heating

The heating of the housing estate by means of central heating was a condition in the Architectural Competition and some kind of district heating was visualized from the outset.

In his analysis of the principal methods of district heating, the late Mr S. B. Donkin showed in his Report to the Westminster City Council, that under the prevailing conditions combined heat and electricity generation would give the greatest economy. This method had the advantage that no heat-generating plant, fuel stores, or chimney need be on the housing estate, so that the whole site can be utilized for housing.

Heat Demand

The blocks of the Pimlico housing estate and also of the Abbot Manor housing estate are built with due regard to a good standard of heat insulation with heat-transmittance coefficients of the walls of 0·2 and 0·25 B.Th.U. per square foot per °F. per hour.

The maximum heat demand for the Pimlico housing estate for space heating was estimated for design temperatures of 65° F. in the living rooms and 55–60° F. in the bedrooms, kitchens, and bathrooms, at an outside temperature of 30° F. For the Abbot Manor housing estate an outside temperature of 32° F. has been assumed, which gives a slightly reduced heat demand. The maximum heat demand for hot tap-water was based on a daily consumption of 15 gallons per head at an average temperature of 130° F.

The total maximum demand for heat for the whole of the Pimlico estate was estimated at about 450 therms per hour, and, including Dolphin Square, Russell House, and the Abbot Manor Housing Estate, at about 750 therms per hour.

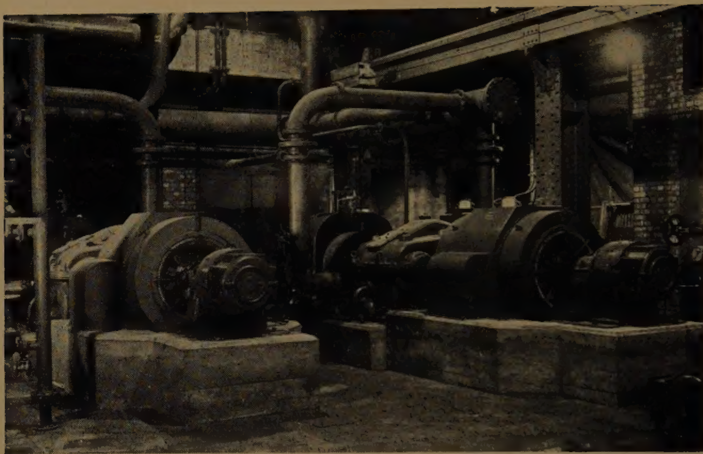
Choice of Heat Carrier

For central-heating installations and for district heating, a heat carrier in the form of steam or hot water is required. After conveying the heat, the heat carrier itself is returned to the boilers or the heat-generating station as condensate or as cooled heating-water to be charged with heat and re-

Fig. 3

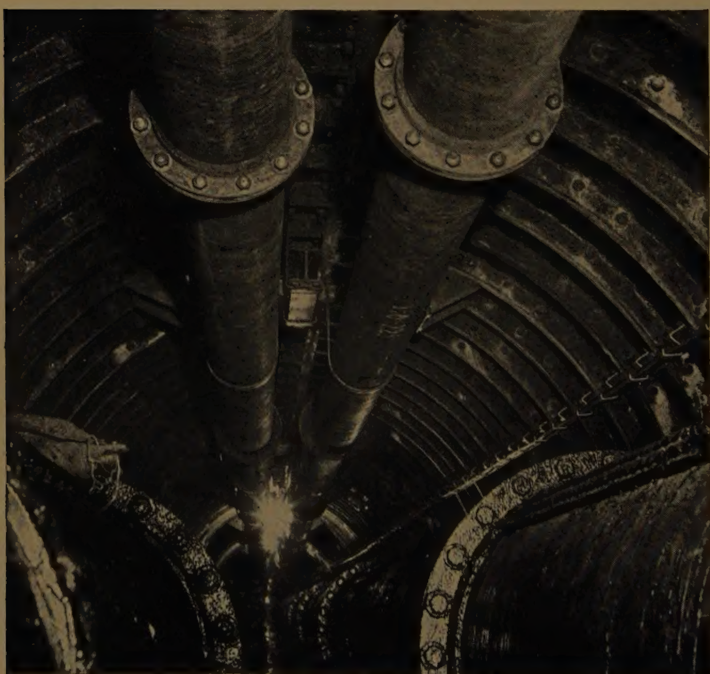
General View of Estate from the South Bank of the Thames

Fig. 5



BACK-PRESSURE SETS AT BATTERSEA POWER STATION

Fig. 7



TRANSMISSION MAINS IN METROPOLITAN WATER BOARD'S TUNNEL UNDER THE RIVER THAMES

Fig. 8

HEAT STORAGE ACCUMULATOR

Fig. 10

MAINS WITH EXPANSION JOINTS IN TUNNEL UNDER GROSVENOR ROAD

Fig. 11

INTERIOR OF SUBSTATION AT CHURCHILL GARDENS

circulated. In contrast to steam with unavoidable condensate heat losses, hot water is an ideal heat carrier. The temperature of the heating water can be varied to suit the variable conditions of weather and of electricity generation. Moderate water temperatures can be used and varied by the back pressure on the turbines in accordance with the heating requirements. The heating water is used as cooling-water and heated in the same way as the cooling-water in condensing stations. The quantity of circulating water per kilowatt generated can, however, be considerably reduced below the requirements of a condensing station, owing to the higher temperature rise, and the condensers and circulating pumps may be reduced in size. It should also be noted that the whole of the energy supplied to the circulating water pumps appears as useful heat in the circulating water, and that the heat of the exhaust steam from the auxiliaries is completely utilized.

A great advantage of using heating-water as a heat carrier is the possibility of heat storage for balancing the independent fluctuations of the heating and electricity loads. The heat losses of a large-capacity hot-water accumulator as required for district-heating plants is, owing to the relatively low surface/volume ratio of large containers, almost negligible ; for large plants the heat losses are less than 1 per cent of the total supply of heat.

General Outline of the District-Heating Scheme

The district-heating scheme is shown diagrammatically in Fig. 4, Plate 1. On the left side of the diagram Battersea power station is shown, in the lower right-hand corner of which two back-pressure turbo-generators with heat exchangers and circulating pumps are indicated. The heating-water is transmitted through heating-mains in the tunnel to the substation at Churchill Gardens. Here, the large-capacity hot-water accumulator is installed for storage of the heating-water. The heating-water is circulated from this point by an independent set of pumps to the flats in Churchill Gardens and Dolphin Square.

Heat-Electric Generating Plant

The chief technical particulars of the combined heat-electric generating plant installed at Battersea power station are as follows :—

Two machines, each of maximum continuous output	1,350 kW.
Exhaust heat, per machine	227·5 therms/hr
Voltage of electric output	3,300 volts
Temperature of heat output	200° F.
Initial steam pressure	600 lb./sq. in. gauge
Initial steam temperature	800° F.
Back pressure of exhaust steam	2 lb./sq. in. gauge
Turbine speed	10,000 r.p.m.
Alternator speed	1,500 r.p.m.

The combined maximum heat output of the two sets is 455 therms per hour, which is sufficient to meet the peak demand of 750 therms per hour ; this is achieved by running the sets continuously on cold days, if necessary

for 24 hours, and by making use of the accumulator to store the excess heat output in the off-peak time and by night as required, and to make up the deficiency of heat output during the day.

Reducing valves and de-superheaters are provided to supply low-pressure saturated steam to the calorifiers from the 600-lb.-per-square-inch steam mains in the unlikely event of an emergency.

Space has been left at Battersea power station for the installation of a third set to meet future growth of heat demand.

Fig. 5 shows the back-pressure geared turbo-alternators at Battersea power station.

Heat Transmission

The crossing of the River Thames by the 12-inch-diameter flow and return transmission mains has been facilitated by the Metropolitan Water Board granting a wayleave through their existing water-supply tunnel for a moderate charge.

The transmission mains on the Battersea side of the river are laid in conduits, but on the Westminster side the pipes are in a tunnel which was specially provided for the purpose on account of the road traffic considerations and a possibility of future rebuilding of the river embankment.

The transmission mains are provided with bellows-type expansion pieces, roller supports, and anchorages, as shown in *Figs 6.* Expansion pieces have been omitted in the tunnel because the profile of each main forms in itself a large expansion bend with an anchorage in the middle of the under-river run of the tunnel.

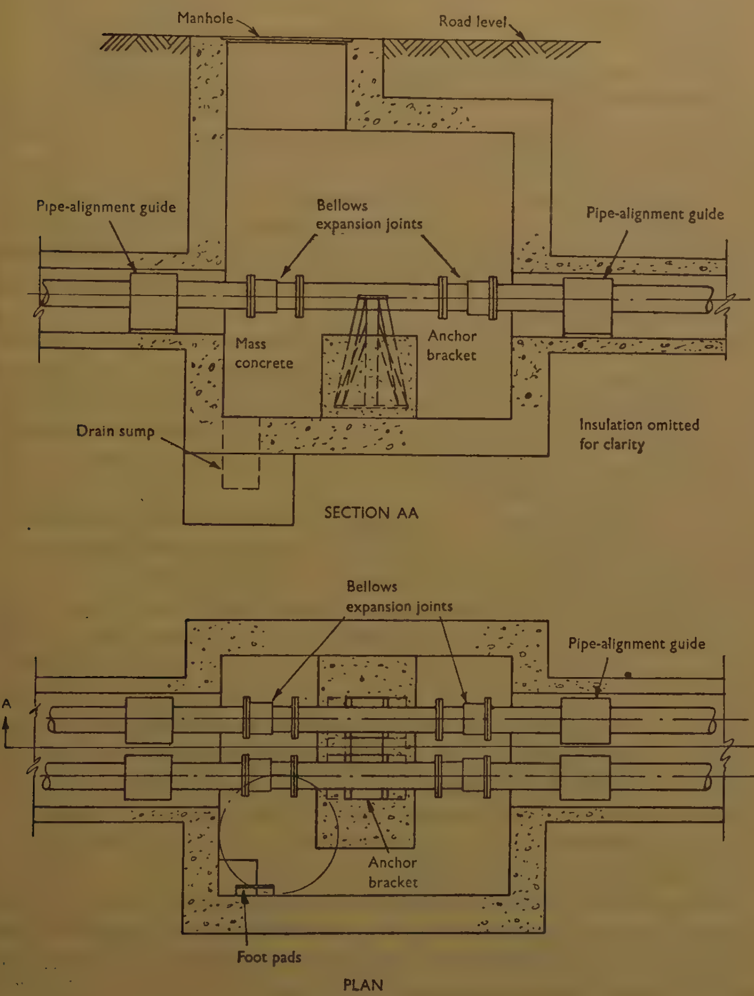
On the Battersea side of the river where the transmission mains are run in conduits they are butt welded. In the tunnel, flanged and bolted joints have been provided, in order to remove any possibility of danger to the health of the erectors from the fumes produced by the welding process. *Fig. 7* shows the pipes in the Metropolitan Water Board's tunnel and *Fig. 10* (facing p. 263) the pipes in the Grosvenor Road tunnel after erection and jointing, but before application of the heat insulation, which consists of a cork sectional covering 2 inches thick.

The Accumulator

The main feature of the district-heating plant is the hot-water accumulator for balancing the heat and electricity loads. The heated water is fed into the top of the accumulator and the cooled water from the heating systems in the flats is fed in near the bottom. When the accumulator is being charged, the cooled return-water is taken from the heating systems to the lower part of the accumulator and transmitted to the heat exchangers at Battersea power station where, after being heated to the desired temperature, it is returned to the top of the accumulator. When the accumulator is being discharged, the heating-water from the top of the accumulator is circulated to the heating systems in the flats, and the cooled

water from the heating systems is fed to the bottom of the accumulator. The same heating-water is in continuous circulation; only the heat of the hot water is withdrawn and no water is wasted. The weight of the total

Figs 6



Expansion Chamber

heating-water of the heating systems and of the accumulator remains constant; only the volume varies in accordance with the temperature. The upper part of the accumulator serves as an expansion vessel for all heating systems, and the initial fill of town water amounts to about 500,000 gallons.

Make-up water is treated to prevent corrosion, scale, or deposits in any part of the system.

The accumulator consists, as shown in Figs 9, Plate 2, of a vertical cylindrical vessel of steel construction with the following dimensions:—

Inside diameter	29 ft
Height	126 ft
Volume	80,000 cu. ft
Effective heat storage for 80° F. rise	4,000 therms
Heat storage per cu. ft	5,000 B.Th.U.

It might be noted that the useful heat storage per cubic foot is about 20 times that of town gas of a declared calorific value of about 500 B.Th.U. per cubic foot, when used at an average thermal efficiency of 50 per cent.

To facilitate the detection of leakage of heating-water in any part of the installations and transmission mains, a minute percentage of fluorescein is dissolved in the water, so that a glow appears when subjected to light from an ultra-violet lamp.

The shell of the accumulator comprises twenty-one courses of mild-steel plate, $\frac{7}{8}$ inch thick in the lower part and $\frac{5}{16}$ inch in the upper part, which is strengthened by stiffening rings inside the shell. Flat rings are welded on the outside to support the heat insulation, which consists of cork lagging 3 inches thick. The lagging is kept in place by nuts and washers on studs welded on to the outer surface.

All joints in the structure of the accumulator were made by arc-welding and selected cross joints were X-rayed. The studs supporting the lagging were welded on to the shell by a special stud-welding process.

The weight of the accumulator full is about 2,400 tons. It is erected on a reinforced-concrete foundation resting on an existing gravel layer. The foundation of the hot-water accumulator is in the position previously occupied by the Belgrave Dock, and borings showed that the estimated loading was perfectly safe. The shell is painted outside with bitumen paint and inside with "Apexior" as a safeguard against corrosion. Special attention was given to the baseplate where it comes in contact with the concrete foundation. The baseplate rests on two layers of "Ruberoid" which serves the double purpose of preventing corrosion and ensuring even contact between base and foundation.

The accumulator is enclosed in a steel-framed glass structure. The enclosure is 138 feet high and is in the form of a sixteen-sided polygon in plan, as suggested by the Architects. *Fig. 8* shows a pleasant architectural harmony between the accumulator structure and the adjacent block of flats.

The enclosure rests on the same foundation as the accumulator but it is otherwise structurally independent. The glazing consists of $\frac{1}{4}$-inch-thick panes set in aluminium glazing-bars.

Apart from its main purpose of enhancing the appearance of the accumulator, the enclosure serves to protect the heat insulation from the weather and it also acts as an additional insulation. Another function of

the enclosure is to provide for access, inspection, and maintenance; for this purpose six 30-inch wide galleries at 18-foot vertical intervals with interconnecting ladders are provided. Provision has also been made for access to the outside surface of the glazing for cleaning by means of a rotating retractable jib with a cradle.

The Substation

The control of the district-heating plant is centralized in the substation. Here all the circulating pumps are installed and all indicating and recording instruments required for running the plant are mounted on a panel.

The temperatures of six selected rooms (twelve when the estate is completed) are indicated and recorded on the panel. Any deviation from designed room-temperature shows that the heating-water temperature is too high or too low. To correct this, the operator varies the thermostat setting of a mixing valve which controls the relative quantities of flow and return water.

The interior of the pump and control room is shown in *Fig. 11* (facing p. 263), and the installed pipework, valves, and meters are shown diagrammatically in Fig. 12, Plate 2. On completion of the housing estate a maximum circulating water quantity of 75,000 gallons per hour at a pumping head of 40 feet will be required.

The system is designed for a temperature difference between flow and return water of 60° F., instead of 20–30° F. normally used for forced circulating systems. This reduces the quantity of circulating water and gives suitable temperatures for the separate control of hot tap-water and space heating at the service points.

Control and Metering

A heat-meter at Battersea measures the heat sent out, and another heat-meter at the substation measures the heat received. For the outgoing heat, two heat-meters are provided, one for the heat supply to the housing estate, the other for the heat supply to Dolphin Square. Experience, however, has shown that the accuracy of the meters is not sufficient for ascertaining the heat losses, and for that purpose a special investigation was necessary. The heat stored in the hot-water accumulator is indicated by a heat-capacity meter. In addition, the temperature of the hot water at six different levels in the heat accumulator is indicated and recorded, and the operator at Battersea power station can be informed by a private telephone of the extent and possible duration of any necessary change of heat storage. No heat-meters are provided for the blocks of flats of the housing estate. The heat supply to these blocks is controlled from the substation by varying the flow-water temperature in accordance with the inside temperatures in a number of selected living rooms. For continuous heating,

as required for dwellings, it is an effective and accurate control of the heat supply.

Heat Distribution

The central position of the substation made possible the arrangement of five separate pairs of mains to the consumers in Churchill Gardens. The supply of heat to each of the five groups of buildings and to Dolphin Square by separate circuits has the advantage of a better control of the heat supply and also easier repair when necessary.

The distribution mains are sited wherever possible in the basements of the blocks of flats. This saves the cost of expensive conduits and reduces the heat losses to a large extent.

The distribution mains are butt welded throughout and flanges are used only at valves. The thermal insulation of the mains is of glass silk in the basements, and of preformed compressed granulated cork in the conduits.

Service Connexions

The arrangement of the service connexions for space heating and hot water is shown in Fig. 13, Plate 2. The heating-water is supplied to each block of buildings at a higher temperature than required for space heating, and is adjusted to the right temperature by an admixture of return water from the radiator system of each block. This is done by passing the service water to the heating system through an injector. The heating-water to the calorifiers for hot tap-water and to the unit heaters in drying rooms is delivered at a higher temperature. One service connexion is provided for each block of flats, but the large blocks are arranged with two service connexions to minimize the temperature drop. The hot tap-water in the buildings is heated in calorifiers to a temperature of 130–135° F.

The principle of temperature control in Dolphin Square, both for space heating and hot tap-water, is the same as for Churchill Gardens.

Safety Precautions

The reliability of a district-heating service is at least as great as that of other public services. In order, however, to ensure reliability, high standards of engineering design, workmanship, and testing are necessary. The standard of work required is higher than that for normal heating installations, because of the great stresses on large mains and because of the relative inaccessibility of mains in underground conduits. This applies particularly to the quality of welding used for pipe jointing. Satisfactory welding appliances and material for welding are readily obtainable, but the reliability of the welds rests almost entirely on the skill of the welders themselves. It is, therefore, important that a careful control is maintained on the quality of each welder's work.

All transmission and distribution mains have been tested hydraulically

to twice the working pressure; heat tests were also carried out to check the mains under working conditions. Provision is made for drainage of conduits and channels carrying the mains. The drains are a means of checking leakage because the dissolved fluorescein, referred to above, distinguishes the leakage from surface water.

As a safety precaution against flooding of the pump-house basement, an electrically operated emergency valve for the accumulator is installed, which automatically isolates the hot-water accumulator in the event of an abnormal drop of its water level, or undue rise of the water levels in the sumps in the basement of the substation and the Thames tunnel. A special control panel already referred to under "The Substation," fitted with water-level indicators and with audible and visible signals, is provided.

Heat Consumption and Rates

The annual heat demand for space heating and hot-water supply for a flat for a normal heating season has been estimated as an average of 535 therms.

The weekly flat-rate charges for space heating and hot-water supply under present conditions are as follows:—

1 room with kitchen and bathroom	4*s*. 3*d*.
2 rooms " " "	7*s*. 9*d*.
3 " " " "	9*s*. 5*d*.
4 " " " "	11*s*. 1*d*.
5 " " " "	12*s*. 7*d*.

Operation of the Pimlico Scheme

Operating Records

The Pimlico district-heating scheme has been in continuous operation for more than 2 years and systematic operating records are available for the period October 1951 to September 1953 inclusive. From these records it is possible to determine the quantities of energy in circulation, and to make an energy-flow diagram, and a heat balance. The heat-energy meters on which the heat balance depends give consistent results and act as a fair check on each other, but their individual accuracies are not so reliable as to permit their differences being taken even as a rough indication of the losses, which are low in comparison with their errors.

Ratio R: Electricity/Heat

The main point of interest about any combined heat-electric scheme is the ratio:

$$R = \frac{\text{Electrical energy sent out}}{\text{Heat energy sent out}}$$

and the weight of evidence indicates that in the case of the back-pressure generators at Battersea, $R = 0{\cdot}17$.

This is borne out by the monthly returns of electricity and heat sent out, from which the figures given in Tables 2 and 3 are extracted. The month-by-month divergencies of R from its average over the 2 years concerned can be taken as a rough measure of the reliability of the electricity and heat measurements, bearing in mind that the figures given for electricity sent out involve an estimated value for auxiliary consumption.

TABLE 2.—PIMLICO DISTRICT HEATING UNDERTAKING

$$\text{Values of } R = \frac{\text{Electrical energy sent out}}{\text{Heat energy sent out}}$$

derived from 24 months' actual operation

Year and month		Electricity sent out				Heat sent out		R	
		Thousands of kWh		Thousands of therms		Thousands of therms			
1951	Oct. . .	446		15·3		88		0·174	
	Nov. . .	516		17·6		102		0·173	
	Dec. . .	580		19·8		119		0·166	
1952	Jan. . .	707		24·2		138		0·176	
	Feb. . .	682		23·3		132		0·176	
	Mar. . .	584	3,515	20·0	120·2	117	696	0·171	0·173
	Apr. . .	462		15·8		92		0·172	
	May . .	244		8·3		50		0·166	
	Jun. . .	233		8·0		46		0·174	
	Jul. . .	215		7·3		43		0·170	
	Aug. . .	220		7·5		43		0·174	
	Sep. . .	257	1,631	8·8	55·7	53	327	0·166	0·170
1951/52 . . .			5,146		175·9		1,023		0·172
	Oct. . .	555		19·0		119		0·160	
	Nov. . .	662		22·6		139		0·163	
	Dec. . .	744		25·4		154		0·165	
1953	Jan. . .	755		25·8		155		0·167	
	Feb. . .	683		23·3		138		0·169	
	Mar. . .	691	4,090	23·6	139·7	140	845	0·169	0·165
	Apr. . .	565		18·9		114		0·166	
	May . .	298		10·3		64		0·161	
	Jun. . .	242		8·3		49		0·170	
	Jul. . .	246		8·4		49		0·172	
	Aug. . .	226		7·7		47		0·164	
	Sep. . .	207	1,784	7·1	60·7	48	371	0·146	0·173
1952/53 . . .			5,874		200·4		1,216		0·165
1951/52/53 . .			11,020		376·3		2,239		0·168

TABLE 3.—PIMLICO DISTRICT HEATING UNDERTAKING

Heat-flow-meter readings and losses as metered and as estimated

	Winter Oct. 1952 to Mar. 1953	Summer Apr. 1953 to Sep. 1953	Year Oct. 1952–Sept. 1953	
			Metered	Estimated*
Sent out from Battersea: thousands of therms	845	371	1,216	—
Received at Pimlico substation: thousands of therms	823	351	1,174	—
Transmission losses: thousands of therms	22	20	42	24
Sent out from Pimlico substation: thousands of therms	794	341	1,135	—
Lost in storage: thousands of therms	29	10	39	13

* Divergencies between measured and estimated losses are presumably due to meter errors.

Energy Flow Diagram

Fig. 14 shows, in round figures, the estimated energy circulating in the form of heat, and mechanical and electrical energy in the main circuits of the Pimlico energy-flow diagram, which conforms with the following six assumptions :—

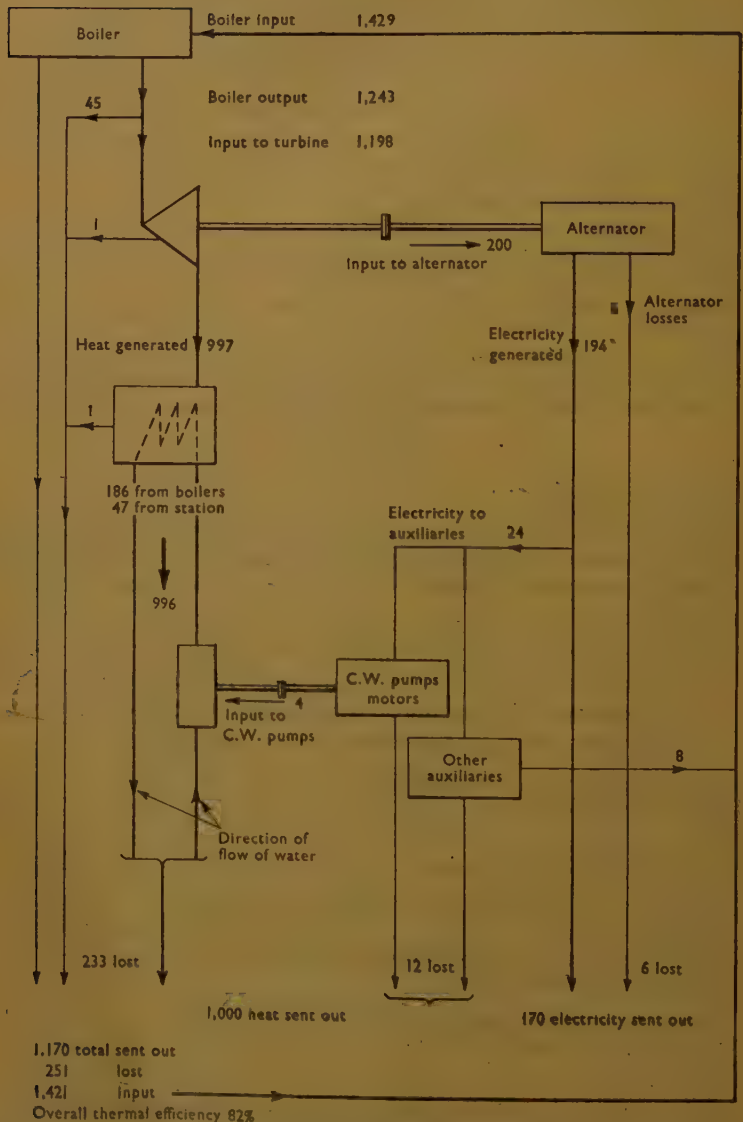
(1) The energy supplied for operation of the auxiliary plant is 2 per cent of the total energy sent out. It appears from Table 2, referred to in the previous paragraph, that the relative values of the energy quantities concerned are as follows :—

Heat energy sent out to district heating	100·0
Electrical energy sent out	17·0
Total energy sent out	117·0
2 per cent of total to auxiliaries	2·4
Estimated energy to auxiliaries as percentage of electrical energy sent out	14·1 per cent
Estimated energy to auxiliaries from operating records as percentage of energy sent out	12·1
Residue to circulating pumps at substation as percentage of electrical energy sent out	2·0 „

which is about twice the actual consumption of electrical energy at the Pimlico substation.

(2) Half the above 2 per cent to auxiliaries is returned, partly as mechanical energy to the circulating heating water and converted to heat by pipe friction, and partly as heat otherwise discarded. It is estimated that the actual return of energy

Fig. 14



ENERGY-FLOW DIAGRAM FOR COMBINED HEAT-ELECTRICAL GENERATING STATION UNDER CONDITIONS SIMILAR TO PIMLICO SCHEME

Figures show energy in units of 0·25 therm per hour

Arrows show direction of flow of energy, except where otherwise mentioned

would exceed half of that supplied, but the difference would have no significance so far as the overall heat balance is concerned. It might be noted that in a combined heat-electric generating station the auxiliary energy returned includes, in addition to the circulating pump energy, a proportion of the energy from all other pumps and fans in the water, air, and gas circuits, and also the heat of auxiliary exhaust steam.

(3) Three per cent of the mechanical energy input to the alternators is lost. This is estimated to be a reasonable average for all alternators, but errs on the low side for Pimlico.

(4) Heat loss from turbine and heat exchanger, and heat returned from circulating water pumps are 0·2 per cent and 0·4 per cent respectively of total heat sent out, as shown in *Fig. 14*, for all values of R.

(5) Four per cent of the heat output of the boilers is lost entirely in the station as radiation and convection from plant and pipework, blow down, soot blowing, drains, etc.

(6) The average thermal efficiency of the boilers is 87 per cent.

These assumptions are not likely to be seriously in error, either individually or in the aggregate.

TABLE 4.—HYPOTHETICAL SCHEMES

Annual heat energy and electrical energy

Values of R	0	0·17*	0·3	0·4	0·5
	Energy in units of 10^4 therms				
Energy sent out					
As heat	1,000	1,000	1,000	1,000	1,000
As electricity	0	170	300	400	500
Total	1,000	1,170	1,300	1,400	1,500
Electricity to auxiliaries	20	24	26	28	30
Electricity generated	20	194	326	428	530
Alternator losses	1	6	10	13	16
Input to alternator	21	200	336	441	546
Input to turbine†	1,019	1,198	1,334	1,439	1,544
Station losses between boiler and turbine	38	45	50	54	58
Output from boilers	1,057	1,243	1,384	1,493	1,602
Input to boilers, including heat from auxiliaries	1,216	1,429	1,592	1,716	1,841
Heat from auxiliaries	6	8	9	10	11
Heat input from coal	1,210	1,421	1,583	1,706	1,830

* $R = 0{\cdot}17$, as for Pimlico.

† See *Fig. 14*.

TABLE 5.—HYPOTHETICAL SCHEMES

Annual coal consumption and cost

Values of R	0	0·17	0·3	0·4	0·5
Annual heat input: millions of therms	12·1	14·21	15·83	17·06	18·30
Coal* consumption: thousands of tons	49	57·5	64	69	74
Cost of coal at 70s. per ton: thousands of £	172	201	225	242	260

* Calorific value: 11,000 B.Th.U. per lb.

TABLE 6.—HYPOTHETICAL SCHEMES

Kilowatt hours per annum sent out
Megawatts sent out, firm and generated.
Annual revenue from sale of electricity.

Values of R	0	0·17	0·3	0·4	0·5
Energy sent out as electricity: millions of therms	0	1·70	3·00	4·00	5·00
equivalent to: millions of kWh	0	49·8	87·9	117·2	146·5
Max. megawatts sent out at load factor 0·5	0	11·4	20·1	26·8	33·5
Firm output: megawatts	0	7·5	13·2	17·6	22·2
Energy generated as electricity: millions of therms	0·20	1·94	3·26	4·28	5·30
equivalent to: millions of kWh	6	57	96	126	156
Max. megawatts generated at load factor 0·5	1·4	13·0	21·8	28·6	35·4
Annual revenue from sale of electricity:					
From firm output; at £6·3 per kW: thousands of £	0	47·5	84	112	140
From kWh sent out; at 0·45d. per kWh: thousands of £	0	93·5	165	220	275
Total annual revenue: thousands of £	0	141·0	249	332	415

TABLE 7.—HYPOTHETICAL SCHEMES

Total capital expenditure

Values of R	0	0·17	0·3	0·4	0·5
Annual boiler output: millions of therms	10·57	12·43	13·84	14·93	16·02
Hourly boiler output:					
millions of B.Th.U. per hr	240	283	315	340	365
thousands of lb. per hr	(207)	(255)	(285)	(305)	(350)
Cost of boilers:					
£ per 1,000 B.Th.U. per hr	1·72	1·82	1·90	2·10	2·70
£ per lb. per hr	(2·0)	(2·0)	(2·1)	(2·34)	(2·8)
Total cost of boilers: thousands of £	413	510	600	712	980
Generators installed: megawatts	1·4	13·0	21·8	28·6	35·4
Cost of generators: £ per kW	7·0	9·5	10·0	10·5	11·6
Total cost of generators: thousands of £	10	124	218	300	410
Boilers+generators: thousands of £	423	634	818	1,012	1,390
Other plants: " "	80	90	98	104	110
Civil work: " "	250	335	400	450	500
Total for station: " "	753	1,059	1,316	1,566	2,000
Distribution of heat: " "	1,500	1,500	1,500	1,500	1,500
Total capital " "	2,253	2,559	2,816	3,066	3,500

Overall Economy

The combined heat-electric generating plant at Battersea was installed as an addition to an existing condensing generating station. It is, therefore, impossible to state definitely what parts of the total capital charges and operating costs of the condensing and back-pressure stations should be allocated to each. For this reason no attempt is made in the Paper to calculate the overall economy of the Pimlico district-heating scheme as constructed, and this section of the Paper is based on estimated prices for the combined generating plant as it could have been constructed, if designed as a self-contained unit. This can be done with sufficient accuracy, because each item of plant is of an established type on which adequate information is available. The distribution costs at Pimlico are known and the estimation of annual charges and operating costs of this part of the scheme can be made on a firm basis.

The estimates of annual charges and operating costs for the Pimlico scheme are readily applicable to the economy of other schemes operating under different conditions of steam and back pressure resulting in different values of the ratio R. This involves the consideration of generators of high thermal efficiencies which could only be achieved in practice with relatively large units of plant. The estimates for other values of R have, therefore, been based on an assumed annual "sent-out" heat of 10 million therms

TABLE 8.—HYPOTHETICAL SCHEMES

Annual charges.
Pence per therm sent out.
Pence per therm to consumer.

Values of *R*	0	0·1	0·17	0·2	0·3	0·4	0·5
Load Factor, 0·5.							
Annual charges in thousands of £:							
Plant at 10 per cent per annum . . .	75	92	106	111	132	157	200
Distribution at 8 per cent per annum .	120	120	120	120	120	120	120
Coal	172	189	201	207	225	242	260
Works costs . . .	43	47	50	52	56	61	65
Total annual costs: thousands of £	410	448	477	490	533	580	645
From electricity: thousands of £	0	83	141	166	249	332	415
Total from heat: thousands of £	410	365	336	324	284	248	230
Price of heat sent out: *d.* per therm . . .	9·85	8·78	8·05	7·78	6·82	6·0	5·52
Price to consumer: *d.* per therm	10·31	9·22	8·46	8·17	7·16	6·3	5·80
Load Factor, 0·25.							
Annual charges in thousands of £:							
Plant as for 0·5 load factor	75	92	106	111	132	157	200
Distribution . . .	100	100	100	100	100	100	100
Coal	98	108	115	118	128	138	148
Works costs . . .	29	32	35	35	38	41	44
Total annual costs: thousands of £	302	332	356	364	398	436	492
From electricity: thousands of £	0	42	70	83	125	166	208
From heat: thousands of £	302	290	286	281	273	270	284
Price of heat sent out: *d.* per therm	14·5	13·8	13·7	13·5	13·1	12·95	13·6
Price to consumers: *d.* per therm	15·2	14·6	14·4	14·2	13·8	13·6	14·3

compared with the actual 1·0–1·2 million therms per annum sent out at present from Battersea, as shown in Table 2. The resulting estimated figures of annual cost have been plotted on *Fig. 15* as a function of *R*. By this method of plotting the results, the variables appear as straight lines

TABLE 9.—COMBINED HEAT-ELECTRIC GENERATION

Required steam conditions and efficiency ratio

Values of R	0·1	0·17*	0·27†	0·3	0·4	0·5
From Table 4 (R = 0·1 and 0·27 added).						
Input to alternator: thousands of therms	1,260	2,000	3,050	3,360	4,410	5,460
Input to turbine: thousands of therms	11,240	11,980	13,030	13,340	14,390	15,440
Efficiency of turbine	0·112	0·167	0·234	0·252	0·306	0·354
Initial steam press: lb./sq. in. abs.	260	610	610	900	1,400	2,100
Initial steam temp.: °F.	600	800	800	900	1,000	1,000
Feed temp.: °F.	200	200	320	360	400	440
Mean effective input temp.: °F.	392	465	495	551	610	665
Mean condensation temp.: °F.	180	216	180	180	180	180
Ideal efficiency	0·25	0·269	0·330	0·367	0·401	0·43
Efficiency ratio	0·45	0·62	0·71	0·69	0·76	0·82

* R = 0·17 as for Pimlico.
† R = 0·27 Pimlico adjusted for lower back pressure and higher feed temperature.

except for the capital charges on plant. The derivations of the graphs follow from the estimates contained in Tables 4 to 9.

The costs are calculated for annual load-factors of 0·5 and 0·25. The load factor of 0·5 is estimated to be attainable by schemes which include an accumulator and an exact control of heat-dispatching as at Pimlico. The low value of load factor is included by way of contrast.

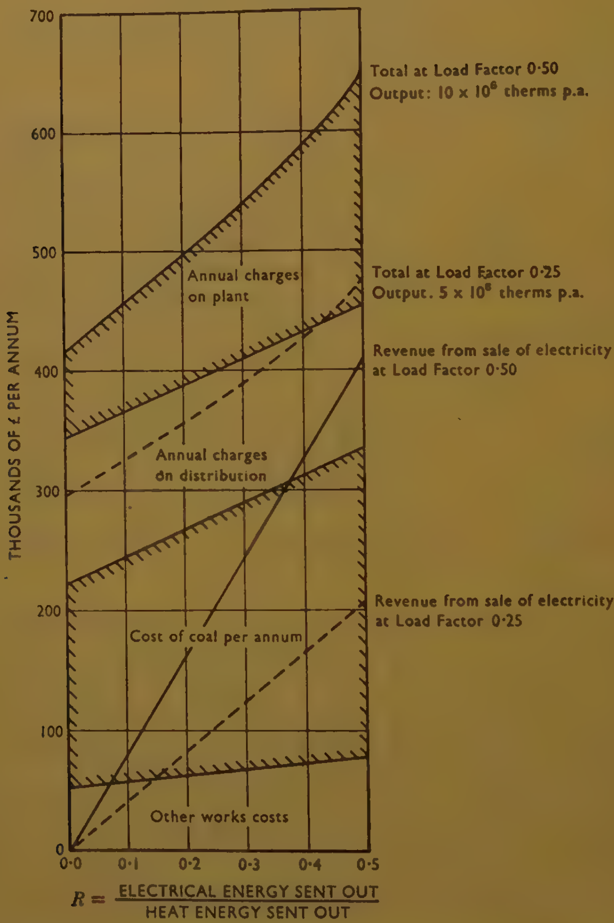
Fig. 15 also includes a graph of the estimated revenue from the sale of electricity. It is based on a two-part tariff of £6·3 per firm kilowatt sent out per annum, and 0·45 pence per kilowatt-hour sent out, based on coal costing 70*s*. per ton and having a calorific value of 11,000 B.Th.U. per lb. The firm output is taken as two-thirds of the installed plant capacity at 0·5 load factor and one-third at 0·25 load factor. The tariff given above accords with costs of electricity production at efficient modern power stations and has been used in a recent authoritative Paper on this subject.[5]

Resulting Cost Per Therm Sent Out

The resulting cost of heat to the consumer is obtained by subtracting the whole of the electricity-sales revenue from the total cost of production and distribution, and dividing by the total heat delivered to the consumers; that is to say, 10 million therms per annum less 5 per cent losses, which

gives the results shown in Table 10. The derivations of these results are given in detail in Table 8.

Fig. 15



Hypothetical Scheme. Estimated Annual Costs of Operation

Heat sent out . . . 10 million therms per annum.
Electricity sent out . . . 146·5 million kWh per annum when $R = 0{\cdot}5$. (See Tables 6, 7, and 8.)

Importance of High Load Factor and Ratio of Electricity to Heat

It is clear from the above figures that it is economically sound to have a high load factor and a high ratio R of electricity to heat, provided that (*a*) the whole of the electricity sent out commands a substantially higher

TABLE 10

Ratio R	Cost per therm delivered to consumer	
	Load factor 0·5	Load factor 0·25
	d.	d.
0	10·31	15·2
0·1	9·22	14·6
0·17 (as for Pimlico)	8·46	14·4
0·2	8·17	14·2
0·3	7·16	13·8
0·4	6·30	13·6
0·5	5·80	14·3

price than the same amount of energy sent out as heat; and (*b*) the incremental annual charges necessary to increase R do not exceed the resulting increase in revenue from the sale of electricity.

For plant of the type installed at Battersea for the Pimlico district-heating scheme, the factors which determine the ratio R of electricity to heat sent out are :—

(1) The mean effective temperature (in °F.) at which heat is absorbed by the water and steam in the boiler and superheater, denoted by T_1.

(2) The temperature (°F.) at which the exhaust steam is condensed at the turbine outlet, denoted by T_2.

(3) The turbine efficiency ratio, that is, the ratio of the heat converted to work in the turbine to the ideal available energy $\dfrac{T_1 - T_2}{(460 + T_1)^*}$

Table 9 shows the actual thermal efficiencies of the steam turbines for values of R ranging from 0 to 0·5, including $R = 0{\cdot}17$, the value obtaining on the Pimlico scheme. Table 9 also shows the initial steam conditions, feed and exhaust temperatures, and the turbine efficiency ratios necessary to attain the above efficiencies. It should be noted that the term " thermal efficiency " is applied here to the ratio between the turbine output of available energy and the turbine input heat-energy, without taking into account the turbine heat output which would bring the thermal efficiency of the turbine to little short of unity.

The achievement of a high ratio of electricity to heat involves the use of

* $(460+T_1) = \dfrac{(\text{Heat of steam})-(\text{heat of feed})}{(\text{Entropy of steam})-(\text{entropy of feed})}$ at turbine stop-valve.

high initial steam pressure and temperature, and a high efficiency-ratio involving a costly design of plant as shown by the increasing rate of rise of capital charges shown in *Fig. 15* and Table 8. It is clear that for values of R exceeding 0·3 the demands on the turbine are becoming rather onerous, and for a ratio of electricity to heat of 0·4 or more, a different steam-cycle from that used at Pimlico would be required.

Relative Economy of Pimlico Scheme

It now remains to examine how the combined heat-electric generating plant installed at Battersea, to supply heat to the Pimlico District Heating Undertaking, stands in relation to the hypothetical figures shown in Tables 4 to 9. The operating conditions at Battersea are less favourable than those assumed for the other stations shown on Tables 4 to 9, because the temperature T_2 at which heat is discarded is 216° F. compared with 180° F. assumed for the hypothetical schemes, which would be equally suited to the heat requirements at Churchill Gardens. Also the efficiency ratio of the actual turbine is only about 0·63 compared with 0·75 which could readily be attained with the larger generating sets of the hypothetical scheme.

The high exhaust temperature of the back-pressure turbines at Battersea permits condensation at a pressure above atmospheric and a consequent simplification of plant at the expense of a serious reduction in the amount of electricity sent out per unit of heat; the lowering of the efficiency ratio leads to a more serious reduction.

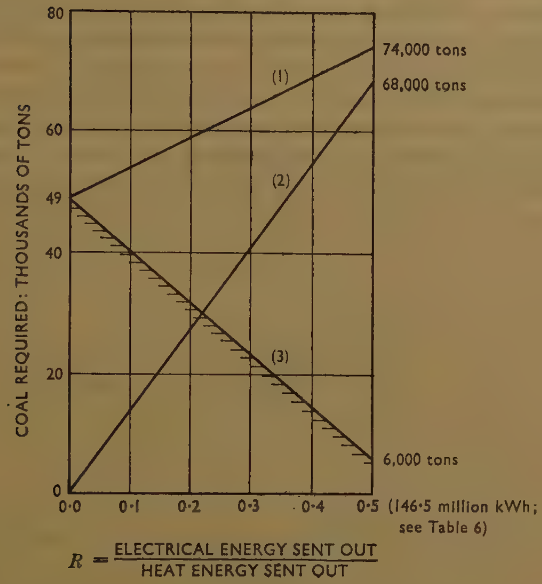
Adoption of the improved conditions of operation would increase the ratio R from 0·17 to 0·27, resulting in a saving in cost of heat delivered to the consumer of 1*d.* per therm and a saving of more than 1,000 tons of coal per annum under present conditions of heat supply by the Pimlico District Heating Undertaking.

The coal consumption of a hypothetical combined heat-electric station, sending out 10 million therms per annum as heat, and $R \times 10$ million therms per annum as electricity, is shown for values of R from zero to 0·5 by Table 5 and by graph (1) in *Fig. 16*. Graph (2) shows the coal consumption of a condensing station of sent-out thermal efficiency 0·3, putting out $R \times 10$ million therms as electricity. The difference between graphs (1) and (2) is shown by graph (3) which represents the extra coal required to send out 10 million therms per annum as heat. The coal for this purpose decreases, in the case of the hypothetical station, at the rate of 8,600 tons per annum per 0·1 increase in R.

In the case of the Pimlico scheme, with a present output of 1·2 million therms per annum, the coal saved by an 0·1 increase of R would just exceed the 1,000 tons per annum referred to above.

The total saving in coal resulting from combined generation under the ultimate scheme (when the heat output is estimated at about 2 million therms per annum) is estimated to exceed 3,000 tons per annum. If

Fig. 16



(1) Coal required for combined generation of 10 million therms of heat energy and $R \times 10$ million therms of electrical energy. (See Table 5.)
(2) Coal for separate generation of above electricity.
(3) Excess of (1) over (2), *i.e.*, the extra coal for combined operation.

COAL CONSUMPTION OF A HYPOTHETICAL SCHEME

account is taken of the elimination of open fires and other thermally inefficient methods of heating, the total saving in coal achieved by the Pimlico District Heating Undertaking will, it is estimated, exceed 10,000 tons per annum for the same quality of heat supplied.

POSSIBLE FUTURE DEVELOPMENTS

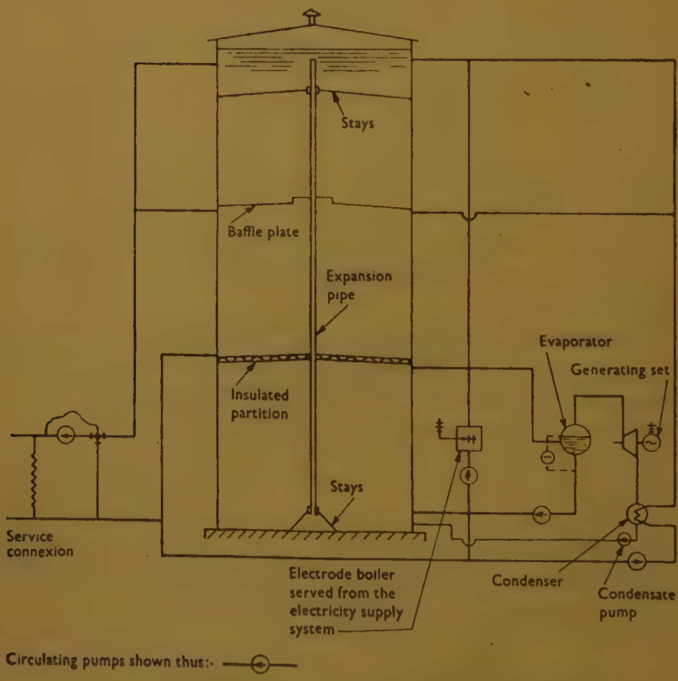
It has been shown[6, 7, 8] that the introduction of the large-capacity hot-water accumulator has created a new economic basis for heat-electric generation and district heating. Both services can be run independently of each other. The annual load-factor of a heat-electric station can be increased to that of a condensing station and the capital charges correspondingly reduced. The capital cost of a large-capacity hot-water accumulator, including insulation, amounts to about £3 to £5 per kilowatt of generating capacity, which is approximately equal to the cost of cooling towers for a condensing station.

An appreciable quantity of power, when not required for the general

supply, can be made available for heating purposes by means of electric-thermal storage. This leads to the system of double-heat storage; first, of exhaust heat at the generating station or substations for districts which can be served from a power station and, secondly, of electric-thermal storage for districts which are too far away from a power station, or which, for other reasons, cannot be conveniently served by exhaust heat.

The system of double-heat storage, as shown in *Fig. 17*, will facilitate the wide application of electricity to all kinds of heating, and so lead to a

Fig. 17



Low and High Temperature Hot-Water Accumulator

complete co-ordination of district heating, electric heating, and electricity supply in general. The heat supply may be extended to isolated groups of buildings by means of hot water accumulators, heated by electrode boilers. In the case of industrial buildings, a proportion of the heat can be supplied with high-temperature hot water for process work which can be stored in the lower part of the hot-water accumulator at a suitable pressure and temperature, which are balanced by the height of the low-temperature water column above the high-temperature hot water. The double-storage

system increases the flexibility of district heating to suit various requirements of heat and of process work with moderate temperatures. Under favourable local conditions, it would even be possible to store high-temperature hot water for the raising of steam which could be used for electricity generation, as by a battery of Ruths accumulators. The steam consumption of the high-temperature process is higher than that with Ruths accumulators, but the steam is produced by back-pressure generation and the secondary exhaust steam is fully utilized. The electricity output is, of course, limited by the permissible height of the hot-water accumulator and by the consequent permissible temperature of the heating-water in the lower compartment. The electricity output is reduced, but the total output, compared with Ruths accumulators, is increased. Owing to the favourable surface/volume ratio of large accumulators and the complete utilization of the exhaust heat, the cost of peak power generation by this method can be considerably reduced.

By means of the large-capacity hot-water accumulator, it would be possible to vary the back-pressure on the turbines and to store the heat in separate compartments of the accumulator at a lower or higher temperature potential, in accordance with operational conditions. The compartments would be separated, where necessary, by insulated partitions, and fitted with expansion pipes terminating at the highest water level of the upper compartment. The increase in the turbine efficiency would be the same as that of a turbine with one or several pressure stages, but this would be attained in the simplest way with one back-pressure unit by variation of the load to suit best the required temperature conditions and to ensure the maximum electricity output.

Single storage of heat makes possible the transfer of heat from a lower to a higher temperature potential. By means of the double-storage system it would be possible to transfer a proportion of exhaust heat into electrical energy. This cycle of electricity generation in a heat-electric station, coupled with the storage of exhaust heat for heating purposes, thermal-electric storage for the heat-supply of isolated areas or even of a remote village with generation of peak power at suitable points, would make possible the future co-ordination of electricity- and heat-supply for large urban areas.

Looking further ahead, the time can be visualized when the scarcity and high price of coal in Britain will compel the adoption of heat-electric generation for all electric power stations located at centres of population and industry, where there would be an outlet for the waste heat. The economical siting of power stations will, in the future, depend on the nature of the load they supply. On the one hand, heat-electric stations will be in or near centres of population ; on the other hand, in order to make use of the vast quantities of very-low-grade fuel which has hitherto been largely a waste product of the collieries, some new power stations will have to be sited at the collieries ; since collieries are rarely centres of big populations,

these stations would have to be mostly condensing stations, for there would be relatively little demand for low-grade heat in such areas.

The elimination from urban atmospheres of the distillation products of domestic coal fires, and the release from the daily task of delivering coal to, and removing ashes from servantless households, may well be a potent factor in attracting families to live in cities within walking distance of their work. The elimination of the costly and time wasting daily travel, often under grossly over-crowded and unhygienic conditions, would give the city worker extra daily leisure, ranging from 1 to 3 hours, which could be used to the benefit alike of the individual and of the community.

The Churchill Gardens housing scheme is an example of housing people close to their work under conditions of comfort and cleanliness and at a price they can afford. Only when the whole of the Metropolis has been re-built on these lines and a smokeless zone established, will the population begin to recognize all the amenities attendant upon district heating.

Conclusions

It is concluded that :—

(1) The Pimlico District Heating Undertaking provides an adequate and reliable supply of heat to the consumers at a cost which compares favourably with other methods of giving the same service.

(2) There is no undue loss of heat in transmission, storage, and distribution.

(3) The economy of the Pimlico scheme is capable of improvement by the increase of the ratio of electricity to heat sent out from the combined heat-electric generating station.

(4) The use of a heat accumulator, as at Pimlico, is essential to the economy of a combined heat-electric system.

(5) The saving in coal by combined heat-electric generation is important to both economy and public hygiene.

Acknowledgements

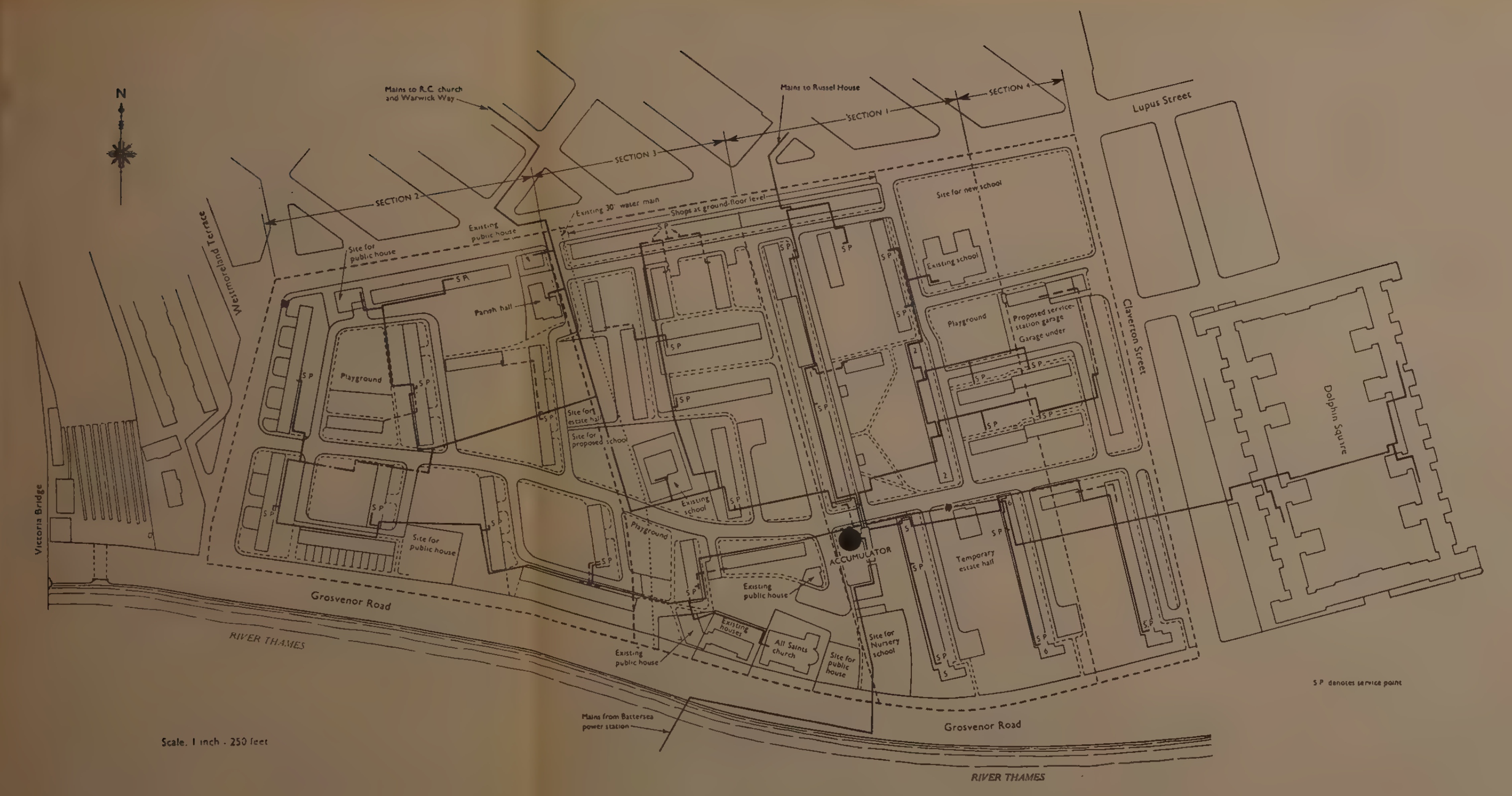
The Authors would like to express their thanks to the Council of the City of Westminster, to the British Electricity Authority, and to many members of their staffs for the information they have made available and the valuable assistance they have given.

Thanks are also due to the staff of Messrs Kennedy & Donkin, and in particular to Mr P. Margen, for their co-operation with the Authors in the preparation of the Paper.

Fig. 5 is reproduced by permission of the British Electricity Authority, and acknowledgement is also due to the Architectural Press for *Figs 8* and *11*.

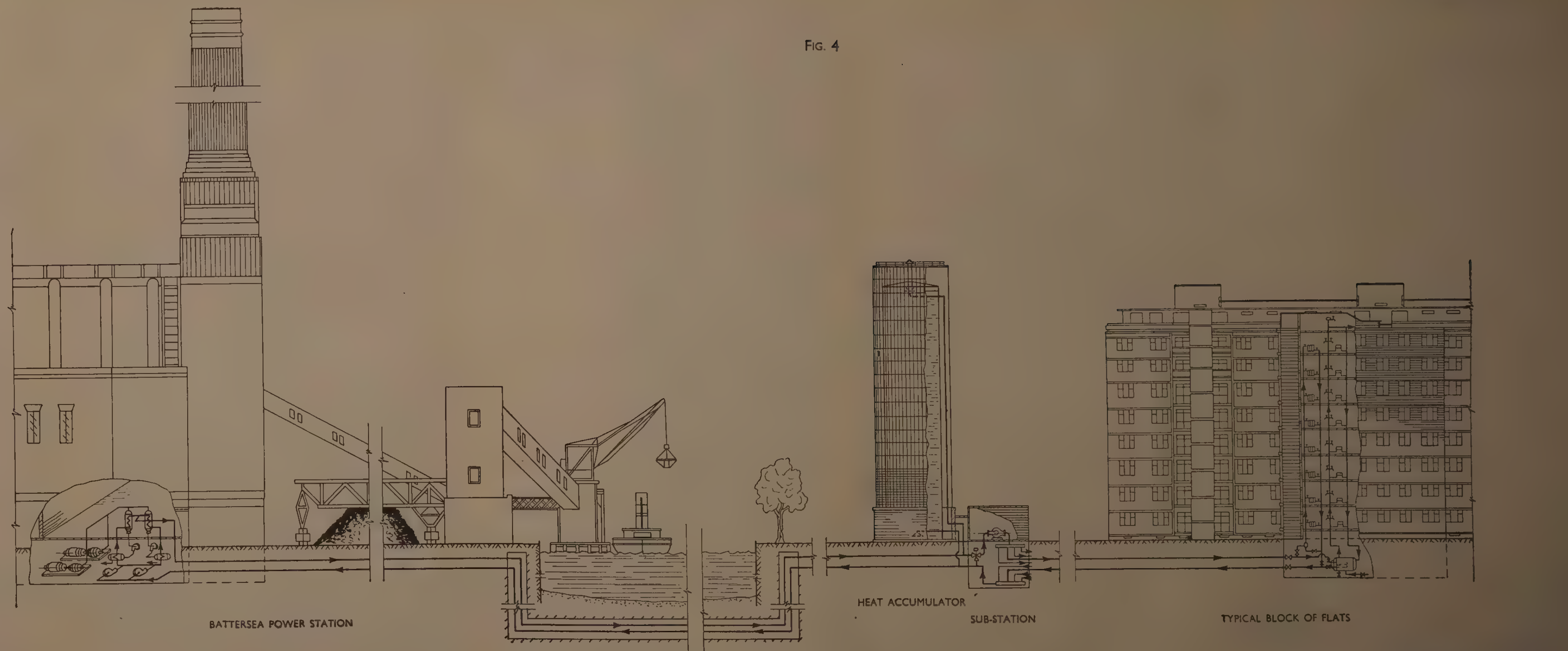
THE PIMLICO DISTRICT HEATING UNDERTAKING

Fig. 2



CHURCHILL GARDENS SITE LAY-OUT

Fig. 4



GENERAL ARRANGEMENT

BRYAN DONKIN, A. E. MARGOLIS,
and C. G. CARROTHERS

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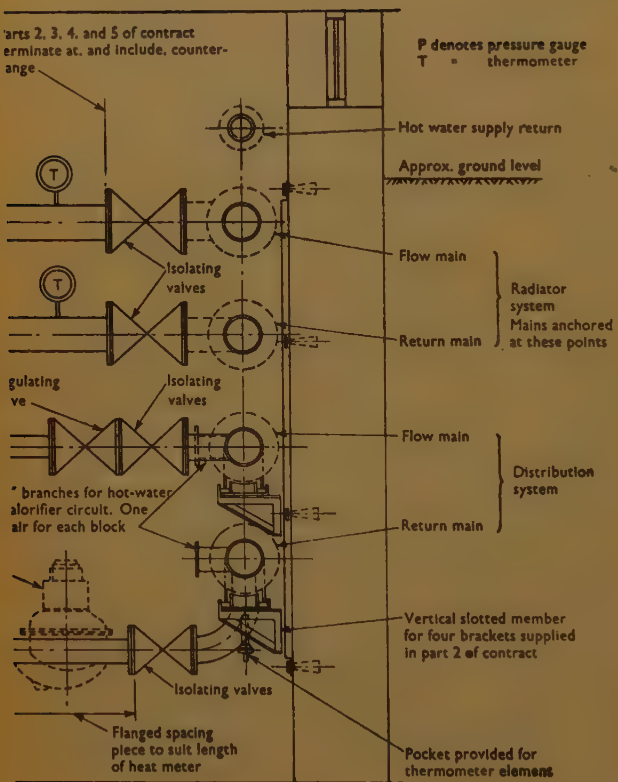

T CHURCHILL GARDENS

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The Paper is accompanied by six photographs and eleven sheets of drawings and diagrams, from which the half-tone page plates, the folding Plates 1 and 2, and the Figures in the text have been prepared.

Discussion

Mr W. W. Ratcliff observed that he proposed to confine his remarks to two of the five conclusions set out on p. 284, namely Nos (1) and (5), or, as he would prefer to put it, Nos (5) and (1). In effect, they claimed that there had been an important saving in fuel and a noteworthy contribution to the avoidance of atmospheric pollution; and that a reliable and adequate supply of heat had been provided to the housing estates at a cost comparable with that of other methods of heat supply. That last claim, of course, had to have an important qualification, because, as was made clear in conclusion (1), the claim was that the comparison was favourable "with other methods of giving the same service."

It would be realized that in the Pimlico scheme, and, so far as he knew, in any other district-heating scheme, whereas a tenant could shut off his radiators for any length of time, he could not shut off the bill; the heat was provided for his use, and he was expected to pay for it.

The City Council of Westminster, when they had been faced at the end of the 1939–45 war with the problem of making good the devastation, decided to follow their usual practice of ensuring that the housing estates which they would build should contain all the reasonable labour-saving devices and amenities which current knowledge made available. So far as heating was concerned, after long discussion and consideration they decided upon district heating to the design of the late Mr Sydney Donkin. Mr Ratcliff was not speaking officially for the City Council, but he thought

that he could say that they did not regret the choice which they had made. On the basis of present experience, if they were asked, they would say that the conclusions on p. 284—in particular Nos (1) and (5), because the others were technical—had been fulfilled.

The Director-General of the Coal Utilization Council, in a letter to *The Times*, had questioned whether there was as yet enough experience to say that district heating was more economical than, as he had said, "the direct use of solid fuel in the home." So far as that alternative means of heating was concerned, land values had dictated that the housing scheme should take the form of fairly high blocks of flats, so that even if solid fuel had been available in the right quantity, at the right time, and at the right price, and also in a smokeless form, it would still not have been acceptable to the tenants.

Mr Ratcliff said, however, that no failure in the scheme had taken place so far, and that conclusions (1) and (5) had been borne out. Between 11,000 and 12,000 persons would live in what was a small township in the centre of London without any smoke going up into the atmosphere from their homes to pollute the air, and about 3,000 families would have no trouble whatever about the supply of fuel. The saving in building costs, apart from the cost of the radiators, would be considerable, because there were no coal cellars, no chimney-breasts, no fireplaces, and no flues from the ground to the eleventh floor.

Many matters of detail had to be considered in carrying out the scheme. One of them arose from the fact that there were no separate flow mains for the hot-water taps and the space heating. Post-war Building Study No. 31 on District Heating had drawn attention to the difficulty in such circumstances of controlling a scheme to suit the temperature of the weather and at the same time keeping a constant hot-water supply to the taps. That difficulty had been overcome at Pimlico. Would the Authors explain how it had been done?

Mr Ratcliff thought that it was only fair to say that the Pimlico scheme which had been decided on by the City of Westminster had started in very favourable circumstances, and the Chairman of the Post-War Building Study Sub-Committee had been right in saying that the Pimlico scheme was to be regarded as the seizing of a convenient opportunity rather than as a typical development.

Mr H. S. Horsman said that the Pimlico scheme, although very important in many ways, was, after all, only a "pilot" scheme, and, in common with pilot schemes it was capable of providing answers to questions which would otherwise be controversial. The scheme should not be judged too critically, therefore, but it should be realized that the venture called for the exercise of courage and a firm belief in the potentialities which it represented.

Referring to that part of the Paper dealing with hypothetical schemes, he suggested that the Authors, in their capital account, had not shown an

item to cover the initial operating period, that was, the period during which revenue was very small, or, perhaps nil, and when, nevertheless, interest payments had to be made; he wondered whether the 7 or 8 per cent on capital, which would be required, was merged in some way in the other components of cost.

Mr Horsman then directed attention to the question of coal savings, as mentioned on pp. 280 and 281. He confirmed the estimate of 3,000 tons per annum for coal saved by combined generation, but with regard to the 10,000 tons saving attributable to the elimination of open fires and the like, he said that was not relevant. The Authors had stated on p. 262 that some form of central heating was a condition of the planning and, that being the case, it was only fair to compare combined generation with central heating. That had been done and the result showed an annual economy of about 5,000 tons. All the foregoing figures referred to the complete scheme and not to its present state of development.

Drawing attention to *Fig. 16*, he thought the principal advantage of the figure would be confined to the range $R = 0{\cdot}3$ to $0{\cdot}4$. His interpretation of line (3) was that when $R = 0{\cdot}58$ there would be no extra fuel costs for allocation to district heating, and therefore if R were further increased, the results as read on the vertical scale became negative. Such thoughts had caused him to examine the assumptions made; they were: (1) a constant efficiency of 30 per cent for the straight electricity station, and (2) a range of terminal steam conditions for the hypothetical schemes as shown in Table 9. The steam pressures, for example, ranged from 260–2,100 lb. per square inch absolute. Line (3) in *Fig. 16* had been recalculated, adopting the same terminal conditions for both types of plant, and it was found that the straight-station sent-out efficiency now ranged from 19·8 per cent to 32·5 per cent in the range of pressures mentioned. The high efficiency of 2,100 lb. per square inch steam pressure would be obtained without the use of reheat, but, by taking advantage of reheat, a sent-out efficiency of more than 34 per cent could be secured from a station operating at the highest pressure in the range.

The effect of these proposed changes would be to convert the straight lines (2 and 3) in *Fig. 16* into curves, the former being convex upwards and the latter concave upwards, and the net result would be that line (3) would never cross the horizontal axis and would probably be more realistic as a basis for assessing the savings arising from combined generation.

Mr Horsman then touched upon the popular topic of atmospheric pollution. It was his view that the Authors could have made more of their opportunity than to dismiss the subject in a few words at the end of the Paper. Churchill Gardens was not a smokeless zone, in the accepted sense of the word, but it was so in the ideal sense. It was true that fuel to supply the heat was consumed at Battersea but the gases were cleansed of dust and sulphur oxides and they were then discharged at the great height of 350 feet above Ordnance Datum. It was clear from that fact

that the much-maligned power-station chimney could play an important part in improving the amenities of a district, as at Pimlico.

Mr J. F. Field said that he was certain that Britain could not afford district heating if it were to be a question of burning fuel in a glorified central-heating boiler. It was too expensive even when using individual boilers, and having a central boiler and distribution system would not make the economics easier. If district heating were to come, it must come in conjunction with electric generation.

The crux of the matter was the ratio R. At Portobello, Edinburgh, electricity was being generated at the rate of one unit per 0·95 lb. of reasonably good coal. (The thermal efficiency, which reached 32 per cent "sent out" during a recent month's run, happened to be the best in the country at the moment; but it was inferior to the best achieved in America.) With a back-pressure plant of any kind it was possible to charge 0·4 lb. of coal per unit to electric power and recover the rest in heat, so saving less than 0·6 lb. per unit relative to best British condensing practice. Thus from the point of view of the electricity-supply engineer the Pimlico scheme would not save more than 2,500 tons per annum; but the real saving was about 10,000 tons, because the heat was used so much more efficiently than in most conventional heating appliances.

The linchpin of any scheme, however, was the ratio R. At Battersea $R = 0{\cdot}17$, but it was comparatively easy to get R up to 0·4, and indeed with existing forms of engineering equipment it should be easily possible to get R up to 0·59. The latter figure was still hypothetical, but easily practicable. It should be possible to get R even up to unity without too much difficulty.

If R were raised to 0·4 in the hypothetical scheme set out in the Paper, it would be found that a therm could be distributed for 2·88*d.*, leaving 3·42*d.* for the cost of the heat at the station end. That was about the same price as the cost of the original coal, so that it saved only the capital cost of separate boilers. The reason the figure was high was fundamental to the use of plain back-pressure plant. When employing back-pressure plant it was usually possible to employ only small units, and it was difficult to get a figure of 0·4, though not impossible with high temperature and pressure. Unfortunately, however, the maximum use-factor of the plant was only 50 per cent, because it could be used only as back-pressure plant and would be standing idle throughout the summer.

The way out of the difficulty was to use a large-size high-efficiency condensing machine adaptable to full-bore back-pressure operation without the necessity to shut it down to effect the changeover, and without losing the advantage of highest possible efficiency under either condition of operation. This could be done by an arrangement which Mr Field proposed to describe in another Paper.[1] Thus it was possible to get a use-

[1] See p. 306.

factor of over 90 per cent (as at Portobello). Such plant could be used as conventional generating plant in mild weather, whilst if hot water was wanted the machine could be switched over to that at night. The great virtue of this idea was that the figure of 6·3*d*. per therm (3·42*d*. production plus 2·88*d*. distribution), which corresponded to the value of $R = 0{\cdot}4$ in the Paper, could be reduced by at least 2*d*. By doing that, an Electricity Authority could make a useful profit and still easily undercut anybody with a back-pressure set. The district-heating schemes proposed at Wythenshawe and elsewhere had the commercial defect that those who promoted them had thought in terms of becoming the owners themselves of back-pressure units of a kind which were not very flexible on the national system.

It could be assumed that a public Electricity Authority would be anxious, naturally enough, not to lose money; their object would be to make progress and to save coal, but not to save coal at any price.

It could be shown that with a dual-purpose set of the kind mentioned above the net cost of the heat was reduced from 3·4*d*. per therm at the sending end to 1·07*d*., thus cutting 2⅓*d*. off the cost. That could be applied to any reasonably concentrated scheme near a major power station. For example, it could be done in that way for Pimlico. The rate of heat output for a typical 60-megawatt condensing set operated in that way was about 4,000 therms per hour, so that with 12 hours' back-pressure use in the winter (it would operate condensing during the day), instead of 24 hours, it could supply heat and hot water to 50,000 people. It was easy to see that enough heat could be made available in London to furnish everybody very cheaply indeed, if the distribution cost was not excessive. The total cost in London could be of the order of 6*d*. per therm; whereas electricity cost about 2*s*., gas cost less but was of far lower utilization efficiency, and the effective cost of coal seemed to be inversely proportional to the age of the grate.

The next problem was how to provide the same benefits to the large number of people who lived far away from the big power stations. Some arrangement was needed to enable the people in a town of 10,000 inhabitants to have those benefits cheaply. That could be done with a gas turbine, the design being modified so that steam was used as the working fluid instead of gas. Mr Field had already described the method.[2] It was possible to run at gas-turbine temperatures and pressures and obtain easily a ratio of 0·59. The essential point there was to get a figure for R higher than 0·4. At 700° C. it was possible to run a gas turbine of that kind with steam, using Nimonic 80A superheater elements. Such an engine had not yet been built, but all the engineering difficulties had now been resolved short of actual building.

The cost per kilowatt would depend on the number of such machines

[2] J. F. Field, "The Application of Gas-Turbine Technique to Steam Power." Proc. Instn Mech. Engrs, vol. 162, (1950), p. 209.

made, and a great number could be used. An engine of that kind, rated at 15 megawatts, would give a back-pressure output of heat of 850 therms per hour—exactly double the output of the two back-pressure sets at Pimlico—and therefore it would produce enough heat to give 20,000 people the same service; but, being out in the country and not near a river or a large power station, "Pimlico"-type hot-water towers would be necessary, adaptable also to be used as cooling towers in summer, when the load was lighter, especially at night. Vapour cooling would be eliminated and electricity alone could be generated at more than 30 per cent efficiency, even without the sale of the heat. That could be the means of saving 50 to 60 million tons of coal a year in Britain for 44 million people. Mr Field did not say that it would happen, but it could happen, and it should be given a trial because Britain was unlikely to have fuel for the 30,000 extra megawatts of plant needed in future for industry unless waste heat was used and the domestic consumption of raw coal was largely eliminated.

Sir Oliver Lyle observed that many people forgot that the only heat which was free in a heat-electric district-heating scheme was the heat that had been put into the condenser, or which would have been put into the condenser had that same amount of electricity been generated in an orthodox station, so that every possible device should be used to raise the value of R. It was deplorable that so much of the heat-drop had been wasted at the Battersea end of the Pimlico scheme. He did not think, however, that that was the important point; the Battersea end was merely a matter of good back-pressure technique, and the trouble there was known and could be put right.

He thought that wrong conditions had been imposed, and that the real problem was at the Pimlico end. There had been a good deal of talk about costs. Costs did not really matter yet; the important information was the customer value of district heat. Gas sold readily at more than four times the price of coal, and electricity sold readily at eight times the price of coal, while those two forms of energy carried with them the dangers of fire, explosion, poison, and shock. District heating was free from hazard, or very nearly so.

Nobody knew the price of district heat. When gas and electricity started they had been faced with the same problem, and until electricity and gas meters of reasonable reliability had been devised nobody knew the customer value of gas and electricity. Gas and electricity, however, had been tried out on the right people, while district heating was being tried out on the wrong people. Looking back over the past 50 or 100 years, it would be found that all new devices or services had been tried out on and developed at the expense of the rich. It would be better to stick to that rule and to let the next district-heating scheme be tried out in a place where the customers could and would pay, such as an office or shop district. There was an ideal site in the City of London between St Paul's and Clerkenwell.

Sir Oliver thought that the Pimlico scheme was a fine fuel-efficiency gesture, but it was not going to provide very much information, except that it had demonstrated the virtue of the heat accumulator. It was not going to tell them the customer value of district heat; nor was it going to induce instrument makers to produce a cheap and reliable heat-meter. With the great prestige of Battersea behind it, many uninformed people would think that the Battersea end was doing all that could be done. Everything possible should be done to make heat-electric district heating work, because from a purely thermodynamic and technical point of view it was the only justification for the generation of electricity by steam.

Mr P. Margen said that the long-term prospects of district heating were bound to be somewhat controversial, so that the main interest of the Paper lay in the economic appraisal of a scheme of a realistic size. Looking through the figures, there were a few points which suggested to him that the appraisal was, if anything, conservative.

One of those points concerned the fixed capacity value which had been allocated to the electricity generated by the scheme. The Authors had credited the scheme with only two-thirds of the capacity value of a conventional station, but he believed that the main point about the hot-water accumulator was that, even with the summer load, which had a minimum monthly load factor of 20 per cent based on the firm capacity, it had so far been possible to cover a peak electric demand equal to the full rating of the plant, and therefore the scheme had a rather higher capacity value than two-thirds of the capacity installed.

Another point was that interest and depreciation had been taken at 10 per cent, which was rather a high value. It seemed to him, therefore, that the aim of the Authors had been to paint a fairly conservative picture; and if, despite that, the cost of heat was competitive with other forms, as it appeared to be from the figures given in the Paper, the conclusion could be drawn that it was time to proceed to large-scale development.

If that view were accepted, and if the Authors' suggestion that a large scheme should be basically similar to Pimlico, with a hot-water accumulator, was also accepted, the next point was the design figures. What sort of steam conditions should be provided, and at what temperature should the heat be discarded? Mr Margen said that there was, of course, an economic limitation to the advantage of a high value of R. If the Authors' approach was adopted of regarding the quantity of heat to be rejected as fixed, the effect of raising the steam conditions was to make more electricity available at the expense of an increase in capital costs. Both the increase in electricity available and the increase in capital costs were precisely the same in a heat-electric station as they were in a condensing station with units of similar size. Therefore economic steam conditions and economic feed-water temperature were practically the same for both forms, so that for a given size of unit the essential design conditions were almost the same.

Another problem was the temperature at which heat should be discarded. That seemed to be mainly a function of the distance of transmission. Long transmission mains became expensive, and it was possible to reduce that expense by reducing the quantity of water circulated, even at the expense of pushing up the temperature of heat rejection and therefore making slightly less electricity available. Hence the temperature of heat rejection should be a function of the distance of transmission.

Mr G. R. F. Nuttall said that in the Ridley Report on fuel and power resources the Pimlico scheme was referred to on p. 131, and the present Paper should be a valuable contribution to the information for which that Report asked. The Report suggested that district heating might be economical in a limited number of cases. Again, in the Electricity Supplement of *The Times* for the current month, Sir John Hacking stated that as a result of the formidable technical problem of finding cooling water, district heating might be helpful when economic schemes could be found. It would be interesting to know from the Authors whether a general survey had been made of densely-populated areas.

The proximity of an existing generating station to a heating load might not be as favourable as at Battersea, and new power stations might be justified. Between the two World Wars he had spent 5 years as an engineer of the Great Western Power Company, which was now part of the Pacific Gas and Electricity Company of San Francisco. That Company had inaugurated a large district heating scheme in San Francisco, using steam for heating. Because of the limited requirements for cooling water and the fact that they had been able to use oil fuel, it had been possible to site those stations under buildings. The fuel was actually stored under the road, owing to the extremely severe fire regulations in San Francisco following the fire of 1906. The economics at that time had clearly shown that it paid to have a number of small units rather than one large one.

According to the Ridley Report, the amount of oil fuel available was likely to be doubled in the next 10 years, but that would probably be absorbed mainly by industry, so that it was doubtful whether much of it could be made available for district heating. An alternative fuel for district heating stations was, of course, atomic power, where 1 lb. of fuel would replace 1,250 tons of coal. That kind of plant might be more easily located to suit local conditions, and could if necessary be below ground. For the benefit of those interested in following American views on that matter, he would refer them to "Economic Aspects of Atomic Power" (Chapter 12, Residential Heating) by Schurr and Marschank.

Mr L. J. Clark said that most of the engineering problems would appear to have been solved, assisted particularly by the use of the accumulator. There was, of course, the unsolved problem of providing a cheap and reliable domestic heat-meter.

The whole future of district heating seemed to hinge on its economics, and in that respect he had been very disappointed to find that the Paper

gave no factual evidence of the actual cost of the Pimlico scheme; instead, the Authors gave estimates in hypothetical cases, which, as many engineers knew, were fraught with many difficulties of conjecture, changing prices and various other unknowns. The Authors had stated that there were difficulties in assessing the cost of the plant at Battersea because it had been erected in an existing station, served by existing boilers and other services. Mr Clark would have thought, however, that a fair assessment of that cost could have been made, and in any case it was likely to be favourable to the Pimlico scheme, because of the existence of the station and the services. Had it been necessary to build an entirely new plant specifically for that purpose, with its own services, it seemed likely to him that the cost would be higher. One inference which could be drawn from the non-publication of costs was that they might turn out to be unfavourable to the plant. Would the Authors, therefore, give more information about the costs?

Dealing with hypothetical cases, the Authors had referred to quite large schemes of about eight times the size of the Pimlico scheme. It seemed to Mr Clark a little doubtful whether in practice such large schemes, serving about 80,000 to 100,000 people, were likely to be as favourable as Pimlico, where the population density was about the highest which would be permitted by the town planning authorities, and which was fairly close to a major power station, with an existing tunnel under the Thames, and where the site had been relatively clear for the laying of ducts and mains.

The Authors had referred to the advantages of going to higher pressures and temperatures on the steam cycle to increase the value of R. That increase of pressure and temperature, of course, also had advantages for the straight cycle, and he did not think that full credit had been given to that aspect in comparing the cost of the two systems.

There was one other aspect which also affected the economics very considerably, and that was the adequacy of the heating system to deal with periods of low temperature caused by cold spells. The plant at Pimlico had been designed to maintain temperatures in all buildings ranging from 55° to 65° F. (say 60° F. average), when the outside temperature was 30° F. in some buildings and 32° F. in others. Perhaps 30° F. might be taken as an average. A statistical examination of meteorological data for the London area showed that in the past 25 years there had been experienced, on an average, 2 consecutive days in every 2 years when the mean daily temperature had been at or below 26° F., and there had been occasions when, for periods as long as 4 consecutive days, the temperature had been lower than 24° F.

On a straight degree/day basis, with an outside temperature of 26° F., it would appear that the Pimlico heating plant as designed for 30° F. was likely to be about 13 per cent deficient in requirements, and at such times of low temperature, the tenants were likely to resort to supplementary forms of heating, probably by electricity or gas. It was interesting to

consider what that meant in terms of energy-supply for the Pimlico scheme. The maximum send-out of heat was 750 therms per hour, of which at least 500 would be required for space-heating. If it were assumed that 13 per cent of that was required for supplementary heating, it worked out as equivalent to nearly 2,000 kilowatts, and the capital costs associated with the generating plant, distribution system and other equipment for such a non-diversified load would be of the order of £100 per kilowatt, and total about £200,000. Mr Clark believed that that figure was higher than the original estimate for the whole Pimlico district-heating scheme. If the economics of heat-supply were to be considered on a national basis, the parochial point of view should be avoided and the overall costs to the community fully appreciated. If a heating scheme was going to be put in, it should be able to do the job completely by itself and not involve very uneconomic demands on other heat services with consequent high costs which were virtually hidden from the normal accounts.

It had already been emphasized that one of the most important aspects of a heat-electric scheme was coal saving, and two figures had been suggested in the Paper for the value of the coal saved, namely 3,000 and 10,000 tons per annum. He thought that the only figure which could really be used for purposes of comparison was 3,000 tons per annum, as Mr Horsman had pointed out. One would not compare heat-electric district heating with normal dwellings with old types of fire.

The problem was how much capital had to be expended to save 3,000 tons of coal per annum. Coal had to be saved, but capital also was scarce and there were many ways of saving coal. Would the Authors, therefore, say more about those capital costs, so that engineers could make a reasonable assessment of which schemes should come first in the priority list for coal saving.

Mr Clark understood that when the Minister of Health had approved the Pimlico scheme he had done so with the proviso that proper costs from both the capital and the operating points of view would be kept.

Mr C. L. Champion observed that the Authors had looked to the generation of electricity as a means of reducing the cost of heat to the consumer. Mr Champion adopted a rather different point of view that since, in a case such as Churchill Gardens, one could not conceive of any satisfactory alternative to central heating, it was of interest to look at the circumstances in which it was economically justifiable to add the generation of electricity to such a scheme.

Adopting the figures for the hypothetical scheme in Table 8, with a value of R of 0·17, it appeared that the extra capital involved for generating plant was about £310,000. The total return on that capital seemed to be of the order of 34 per cent per annum. That figure might be regarded as optimistic. However, a recent Paper by Prosser and Pedder (reference 5, p. 285, based on what would appear to be rather pessimistic considerations, gave a figure of more than 20 per cent for a scheme of similar size. It was

thus well established that the combined generation of heat and electricity was advantageous for saving fuel and reducing fog in cities, and at the same time was also a very good investment.

Why, then, were there no major schemes of that sort in Great Britain? He thought the difficulty lay in the fact that the hypothetical scheme was about five times larger than Pimlico. It would be extremely difficult to find many sites really convenient for a development of that size, and the capital cost of providing heat to districts at present relying mainly on conventional methods of heating would be very considerable. Even so, it would need ten of these larger stations to provide the output of a normal power station. Mr Champion thought, therefore, that it was not possible in the foreseeable future to expect that any considerable proportion of electric power in Great Britain would be produced from heat-electric stations. On the other hand, it was certainly important that all convenient schemes should be developed, and from that point of view it would be extremely unfortunate if those who rebuilt the bombed areas in the City of London failed to utilize heat from Bankside power station.

In schemes of the size of Pimlico, if steam could not be obtained from a nearby power station and where the electricity generated had to be sold to the Grid, it was improbable that they would give more than marginal economy; marginal in the sense that their yield on capital would only be sufficient to pay the fixed charges. If, however, the scheme was such that the owner of the plant could use a large proportion of the electric power supplied, it would be logical to charge that at, say, 0·9*d*. per unit instead of the 0·45*d*. which would otherwise be applicable. In that case a considerable range of smaller schemes would become economically justified.

Mr Champion had recently been concerned with an establishment rather smaller than Pimlico, where the annual load factor had been poor, because heating was not required during the summer months. Nevertheless, it proved that a small turbo-alternator could very well be justified, because the whole of the electricity generated could be used locally. The value of R for that set was less than 0·1 and he pointed out that the return on capital was higher when R was small, so that it was only in the case of the larger installations that it was worth while seeking a high value of R.

There was another point which was of considerable importance in connexion with heat-electric generation. It was well known that some of the collieries in Great Britain were at present producing coal at a loss of more than £2 per ton. It was really the saving of coal at the marginal cost of production which was important from the point of view of the national economy, but, of course, since coal was in fact sold at an average price the owner of the plant could not take that into account when considering the economics of local generation. Nevertheless, that would possibly justify some special national compensation for, or encouragement of, the expenditure of capital on schemes of combined generation.

Mr D. J. Bolton expressed the opinion that the one statement in the Paper which ought to be squarely controverted was the first conclusion on p. 284, where the Authors said "It is concluded that (1) The Pimlico District Heating Undertaking provides an adequate and reliable supply of heat to the consumers at a cost which compares favourably with other methods of giving the same service." Whilst he did not dispute that statement, he felt that it was not a conclusion from the Paper. To prove the statement it would be necessary to have the cost both of generation and distribution; and whilst, no doubt, it was not the Authors' fault that neither set of costs was given, their absence from the Paper made it impossible to prove conclusion (1).

In the absence of those realistic facts, the Authors had taken an imaginary Utopia in which a heat load ten times larger than the present Pimlico scheme would be demanded by a hypothetical consumer and as eagerly supplied by the undertaking. The only justification for that rather large assumption was to enable the calculations to have the benefit of what the Authors called ". . . the consideration of generators of high thermal efficiencies which could only be achieved in practice with relatively large units of plant." In other words, the reason for choosing a large size was because it gave a good efficiency, and not because it could be realistically expected to arise. Where were such large consumers of heat to be found on the doorsteps of generating stations, and was it realistic to assume a linear relationship between distribution costs and load when the load was so large that it was necessary to bring in more distant people to use up the heat?

In Table 8, if R was 0·17, the distribution capital charges, without any operation or maintenance, came to 3*d*. per therm at 50 per cent load factor, and 5*d*. per therm at 25 per cent load factor. On p. 269, it was stated that the tenant paid about 10*d*. per therm overall, so that 5*d*. per therm for the capital charges of distribution would absorb about half the revenue.

The Authors rightly pointed out that the introduction of a large capacity hot-water accumulator had created a new economic basis for heat-electric generation and district heating. Mr Bolton was sorry that the Authors had followed conventional lines in treating load factor as a single entity, whereas in fact it was a complex figure made up of at least two components multiplied together. Putting the matter in its simplest form, if L denoted the daily load factor for the day on which the biggest heat load occurred, and if F denoted the ratio between the average day and the heat on the day of maximum load, then the annual load factor was $L \times F$, the product of two factors each of which was less than unity.

One of those factors could be varied by means of a heat accumulator and the other could not, and therefore it was of little use to discuss the product. If L was 0·5, and if the ratio between the heat on the average day of the year and the heat on the day of the biggest load, F, was 0·6, then the annual load factor was the product of the two, namely 0·3. By

installing an accumulator it was possible to bring the daily load factor up to 100 per cent, which made $L = 1$, but F would still be 0·6, so that the annual load factor was only 0·6. Only the first part of the load factor would be altered. The reason was, of course, that the only way to control F would be to have an enormous insulated heat accumulator (about the size of Loch Ness), which would provide a seasonal flywheel, instead of merely a daily or weekly one. In the absence of that, the Pimlico heat accumulator was functionally not different from a gasholder in a gas supply system.

The Authors had pointed out on p. 281 that "The annual load-factor of a heat-electric station can be increased to that of a condensing station. . . ." Mr Bolton disputed that. It could be increased only up to the point where the daily load factor was 1, and if the ratio of summer to winter usage limited the figure to C·6, it was not possible to go beyond that. The Authors had completed the statement by saying that ". . . the capital charges were correspondingly reduced," and had implied that the heat-electric station and accumulator should be designed at the highest possible daily load factor. That might be true, but it should not be assumed. If a small back-pressure set were installed and run uniformly day and night, taking no notice of the fluctuations of heat demand, there would be a daily load factor of 100 per cent, and the capital charges would be reduced, but the kilowatt contribution to the peak would also be reduced. If the set was larger and was run for 3 hours a day during the peak it might prove commercially more attractive; one could not say without investigation. Fundamentally it was a question of whether back-pressure generation was an economic way of generating kilowatt-hours or kilowatts.

Mr Bolton concluded by saying that there appeared to be some ambiguity in the second half of Table 8. All the columns of Tables 4, 5, 6, and 7, and the top half of Table 8, seemed to have a common basis; they all referred to 10,000,000 therms sent out. The second half of Table 8, however, referred to 5,000,000 therms sent out and was different from all the others. Would the Authors comment on that?

*** **Mr B. D. Richards** thought that some particulars of a large district heating scheme in Iceland, with which he had been associated would be of interest. That scheme, proposed by the Municipality of Reykjavik, was for the heating of the town by hot water from the hot springs at Reykir about 16 kilometres (10 miles) distant. It had been the intention of the Municipality to obtain the finance in London, and C. S. Meik & Halcrow (now Sir William Halcrow & Partners) had been invited by them to investigate and report on the scheme. Mr Richards had proceeded to Iceland in 1937 and prepared a report. Treasury restrictions, however, had prevented the financing of the scheme at that time. The

*** This contribution was submitted in writing after the closure of the oral discussion.—Sec. I.C.E.

matter had been one of urgency to the Reykjavik Municipality and eventually they had secured the money in Denmark and carried out the undertaking themselves.

The scheme comprised :—

(1) Deep borings at Reykir to increase the natural supply of hot water outflowing there.
(2) Piping of the hot water to a sump.
(3) Pumping plant.
(4) Insulated main pipe-line.
(5) Insulated service reservoir near Reykjavik.
(6) Insulated distribution system comprising main pipes and branch pipes to the various buildings.

The scheme was for the supply to about 3,000 buildings holding a population of 30,000, and had visualized a supply of 250–300 litres per second, of which there had been at the time a visible supply of 150 litres per second. The average temperature of the water was 85° C.

After consideration of various insulating materials, it had been decided to lay the pipes above ground and insulate them with cellular concrete, the whole being covered with a layer of shingle, to act as a drain, and surrounded by a bank of turf. The service reservoir was situated on a hill overlooking the town, ensuring a gravity supply. It consisted of a pressed-steel tank insulated to give a negligible loss. The pipe from the service reservoir to the edge of the town was similar to the main pipe, but from thereon the pipes beneath the streets were laid in a Portland-cement concrete culvert and insulated with slag wool.

The system had been designed for the following temperature losses :—

	Temp : ° C.	Loss : ° C.
1. At springs	85·0	
2. At sump	84·7	0·3
3. At service reservoir . . .	82·7	2·0
4. At houses	81·4 av.	1·3
Total loss . . .		3·6

the figures being based on the scheme working at full capacity with a minimum air temperature of —18° C.

During construction of the scheme, some modifications had become necessary, for the 1939–45 war had broken out and certain materials had not been available.

The " soap " for making the cellular concrete had not been obtainable but the Municipal engineer had found a good local substitute for cellular concrete insulation in a special grass, the matted roots of which formed a close fibrous material. That had been placed round the pipes which were encased in a Portland-cement concrete culvert.

Notwithstanding war conditions, the scheme had been completed, and

although its cost had greatly increased, it had proved a valuable scheme, since the cost of imported coal had meanwhile risen to £7 a ton.

Mr Richards, in a visit to Iceland after the war, had had the opportunity of seeing the scheme then in operation, with Mr H. Sigurdsson, the Water Engineer to the Reykjavik Municipality who was responsible for carrying it out.

Mr C. G. Carrothers, in reply, said that finding some use for heat-electric plant in seasons of low heat-demand was one of the problems which had exercised the minds of engineers designing. If Mr Field's invention could be put into effect, it would provide a means of doing that. Other means had been suggested, but few of them had the simplicity of the idea shown by Mr Field, and it would be very interesting to see it in service.

Mr Horsman had referred to the absence of an item in the capital expenses to cover interest paid during construction. That had not been included as a separate item, but it was included in the very ample capital charges allowed for the plant and also the high capital charges, 10 per cent in the case of power-station plant and 8 per cent for distribution.

Mr Bolton had raised the question of which was the by-product, the heat or the electricity. Mr Carrothers thought that that was a question which could not be answered. The first Paper referred to in the list of references was a Paper on electricity as a by-product of heat, but to-day there was a tendency to look at the matter from the point of view of heat as a by-product of electricity. Actually he thought that the whole problem should be integrated and the overall picture displayed; that was what had been attempted in the Paper.

Mr A. E. Margolis said that the need for district heating in the United Kingdom was much greater than on the Continent, and the conditions for the general introduction of heat-electric generation were very favourable. Owing to the climatic conditions, the heat could be distributed by means of hot water at moderate temperatures, and co-ordination with electricity generation was simple and effective. The capital cost of the heat-electric station was not greater than that of a condensing station with cooling towers. The latent heat of the steam was not wasted with the cooling water, and the heating water could be stored in large-capacity hot-water accumulators for later use. The supply of heat and the supply of electricity were thus made independent of each other.

The subject of district heating was complicated, and it was easy to criticize and suggest improvements. It was well known, however, that a combination of heat and electricity production was the best way of saving coal. Mr Margolis thought that he had overcome most of the difficulties by storage of heat, and gas engineers knew very well what an advantage it was to be able to store the production of the works for use later and to be able to balance out production and demand. Unfortunately electrical engineers did not always accept that.

The special attention which he had given to a system of double heat

storage would probably have been noted. It had been remarked that there was nothing new in the system, because a heat-electric station with a hot-water accumulator or domestic hot-water heaters at the consumers' premises represented a double-heat-storage system. That was not quite so, and he could illustrate the difference by a simple comparison of the cost. The cost of a 20-gallon hot-water heater, including installation but excluding purchase tax, was to-day about £50. The hot-water accumulator at Pimlico had a capacity of 500,000 gallons, equal to the storage capacity of 25,000 domestic water heaters, but the cost of that large-capacity hot-water accumulator, including enclosure and heat transmission and distribution to all buildings, was of the order of £250,000, whereas the cost of 25,000 domestic heaters would be £1,250,000.

On the Pimlico district-heating plant, approximately £1,000,000 in capital cost had been saved by heat storage, but some electrical engineers still said that district heating was too expensive and that the nation could not afford it. The development of district heating with the double-storage system would, in the final stage, solve the problem of electricity generation at a nearly constant load. In his Paper on district heating before the British Association for the Advancement of Science last September, he had concluded with a statement that an annual saving of 20,000,000 tons of coal should be aimed at, and he sincerely hoped that the Pimlico District Heating Undertaking would encourage that development.

Mr Bryan Donkin, who also replied, said that several speakers had referred rather pointedly to the absence of any economic figures in the Paper. It should be pointed out that only the first section of the district-heating scheme described was now in operation, and there were three more sections still to come. That was one reason why no economic figures were yet available. It had already been agreed, however, between the Westminster City Council and the British Electricity Authority jointly to undertake an economic analysis of the operating results of the Pimlico scheme, and he was quite certain that the results of that economic analysis, when it had been carried out, would be made public in some suitable form.

Mr Ratcliff had drawn attention to the absence of metering for individual consumers and the inability of consumers to shut off their radiators. In that matter the heat supply resembled the water supply, the cost of which appeared in the rent, independently of the actual quantity of water used. The heat supply might be looked upon as an integral part of the premises rented and just as much part of the amenities provided as the roof.

It was very gratifying to the Authors that Mr Ratcliff should refer particularly to conclusions (1) and (5) as being supported by experience, though these conclusions had been criticized by other speakers. He had also confirmed that trouble free operation had been obtained and that the promises of comfort and convenience had been fulfilled.

With regard to the difficulty of providing constant hot water at the

taps whilst maintaining the appropriate space heating temperature—a difficulty which normally occurred with a two-pipe distribution system—it had been necessary to make special provision for the local independent control of the heat supply to the radiator systems.

By the means of special devices installed in each space-heating service connexion shown in Fig. 13, Plate 2, the amount of heat supplied to the flats could be varied in accordance with the weather conditions as indicated by the flat room temperatures shown on the control panel in the sub-station. Since that variation was made independently of the heat supply to the calorifiers the temperature of the water supplied to the taps was not affected.

The special devices in the space-heating service connexions were remotely controlled at the substation by the transmission of pressure impulses in the circulating water of the distribution mains.

Mr Horsman, in common with a number of others, had questioned the validity of the claims for coal saving illustrated on *Fig. 16*, and in particular the ultimate saving of 10,000 tons per annum. The use of the term "saving" could be misleading unless it was made quite clear on what the saving given in the Paper was based. It might be made clearer that in the Paper the figure referred to as a "saving" was the difference between the total coal for the combined heat and electricity, and the coal required to produce the same services by means of domestic heating appliances of 50-per-cent thermal efficiency and electricity generation of 30-per-cent thermal efficiency. Both of those assumptions for the separate supplies represented very good standards which were not likely to be attained generally in Britain during the next 10 years.

Mr Horsman's suggestion that comparison should be made in each case for generation of electricity with the same initial steam conditions, would in the Authors opinion, be unduly favourable to combined heat-electric generation in the case of Pimlico, where the electricity supply by condensing generation operated at the high thermal efficiency attained by Battersea Power Station.

Mr Field also had referred to the question of the amount of coal saved and the difference in his estimate from that given in the Paper was explained by his different basis of calculation.

Mr Field's suggestion to improve the use-factor by a double-purpose machine, operating either condensing or back-pressure, would undoubtedly improve the economy of combined heat-electric generation. It should, however, be borne in mind that there was bound to be some plant not fully employed at all times of the year, whatever devices were used to reduce the amount of idle plant.

Mr Field's remarks on the application of gas turbines to district heating, using steam as a working fluid, showed that there was promise of district heating by combined generation in all situations, where a reasonable population density existed, whether or not there was a major power station in

the vicinity. Such a development would be a great improvement on the economy attainable by orthodox steam plant.

Sir Oliver Lyle's remark " that the only heat that was free was the heat that had previously been put into the condenser " was very timely. There was occasionally a tendency to forget that all the heat used in combined heat-electric generation had to be paid for and that neither the electrical or the heat output could be looked upon as a gift.

In considering the steam and exhaust conditions chosen for the Pimlico scheme it might be remembered that it had been a primary consideration that the back pressure sets should in no way interfere with the normal operation of Battersea Power Station and in particular there had to be no possibility of aeration of condensate. That had involved some sacrifice in heat drop and a better performance could have been obtained if the design had been completely free from the restrictions referred to.

Sir Oliver had drawn attention to the importance of customer value and had mentioned the City of London as a likely site for applying district heating. He had referred to what the customer " could and would " pay in such an area, but in the Authors' opinion it was what the customers would need to pay if they wished dense centres of population to remain habitable.

Mr Margen had commented on the conservative estimates of firm capacity and capital charges on which the economics of the Paper were based. It had been the Authors' aim to choose figures which could be readily substantiated but it was obvious that the economic position would be very much improved by making less burdensome assumptions.

The Authors were particularly grateful for Mr Margen's exposition of the fact that the economic conditions of initial steam and feed were practically the same for combined generation and condensing generation. The clear understanding of that theorem cut out a number of complicated questions which had previously been in doubt.

With regard to the temperature of transmission and heat rejection, it was the Authors' opinion that practical considerations would always have a major influence on the value to be adopted, though it was of course obvious that other things being equal, the lower those temperatures the better.

So far as the Authors were aware, no systematic survey of densely populated areas suitable for district heating had been put in hand. Naturally considerable interest had been taken in that question, but attention had chiefly been given to the possibility of economic developments on new towns and housing areas. Several large towns, such as Bristol and Coventry, had come under detailed review during the planning of reconstruction after the War.

The results of experience with oil-fired district heating in San Francisco were of very great interest, but it might be noted that a scheme of the type described by Mr Nuttall, using a large number of small units, would be

very much less attractive if coal were used rather than oil. The transport and handling of coal and ash would in such a case present a major problem.

No doubt the future would see many important developments and in years to come atomic power might play an important part. It seemed unlikely that such developments would take place during the life of the Pimlico District Heating Scheme.

Mr Clark had referred again to the question of a cheap and reliable domestic heat-meter. In the case of the Pimlico District Heating Scheme, it had been the aim of the designers to produce a scheme in which the heat supplies could be regulated to suit the customers requirements without undue waste caused by residents using excessive hot water. Experience had shown that that had been generally successful but a careful watch would always have to be kept on heat consumption. That was one of the main purposes of the control room at Churchill Gardens.

Mr Clark, like several others, had commented on the lack of facts concerning the economy of operation of the Pimlico District Heating Scheme and suggested that further assessment of the cost could have been made. Such assessments had in fact been made but had been based on such a large number of debatable assumptions that agreement between independent estimates was never attained. It had therefore seemed desirable to make a straightforward estimate based on well established costs, as explained in the Paper. There was no doubt that the costs at Battersea would be less than the estimates for the hypothetical schemes.

With regard to the possibility of finding a suitable concentration of 100,000 people where district heating could be applied, it might be noted that Pimlico occupies about 60 degrees of the arc of a circle of about ½ mile radius from Battersea Power Station and it would be possible to find room for at least ten such schemes within a radius of 1½ mile. In that connexion reference might be made to *Fig. 1* which showed the populous nature of the area on both banks of the river within the above radius.

Mr Clark had also referred to the possibly unfair comparison of very-high-pressure district-heating schemes with condensing stations operating at lower pressures, but it might be noted that *Fig. 16* in which those comparisons were illustrated should be read in conjunction with *Fig. 15* which showed the limitation in the economic value of R by the capital charges on the generating plant involved.

Mr Clark had rightly pointed out that the use of electricity for dealing with extreme peaks of heat demand would be uneconomical in the extreme. It was partly for that reason that the Pimlico Scheme provided for the direct supply of steam to the calorifiers as shown in Fig. 12, Plate 2, and referred to on p. 267. The use of those direct connexions would remove the need to fall back on electric heating, whatever the outside temperature.

Mr Clark had made the same criticism of the estimated saving of 10,000 tons of coal per annum by the ultimate Pimlico District Heating

Scheme as several other speakers. That point had been dealt with in the reply to Mr Horsman.

With regard to the overall economy of the scheme, it was hoped that in the near future a full report would be available.

Mr Champion had adopted a different approach from that of the Authors to the economic problem, in that he did not give the whole of the benefit of the capital and running charges due to heat-electric generation to the heat consumer. That question had also been referred to by Prosser and Pedder.[5] In strict fairness it might be claimed that the advantages should be shared between the heat and electric consumers, but in a case where the heat and electric consumers were the same people no conflict of interest was involved. In one case, however, Mr Champion had suggested that the electricity consumer should pay 0·9*d.* per unit under combined generation instead of 0·5*d.* per unit, at which price electricity could be purchased from the National Grid. That would appear to subsidize the heat user at the expense of the electricity-supply interests.

Mr Bolton had pointed out quite correctly that conclusion 1 was not supported by an exact balance sheet. It was, however, based on careful estimates of costs obtained in actual practice and it was shown that there was such a wide margin of economic advantage that it appeared to be a reasonable conclusion that an equal advantage would be obtained by the Pimlico Scheme, where part of the plant concerned in the back-pressure generation had already been in existence before the scheme was started.

Mr Bolton had suggested that the magnitude of the heat demand estimated for the hypothetical schemes would only be found in Utopia. That point had already been dealt with in the reply to Mr Clark's remarks, and the Authors were in no doubt that a larger scheme than Pimlico would in fact show lower distribution costs. The individual mains and distributors would be relatively longer with the large scheme, but the increase in expenditure on that account would be offset by the more economic sections of the mains that could be employed and by the reduction in overheads such as capital charges on heat storage, pumping plant, and management.

Mr Bolton's remarks on load-factor appeared to coincide with the Authors opinions on that subject. It was not intended to advocate operation at load-factors exceeding the maximum possible values computed by him.

With regard to the optimum load-factor it would be possible to increase the kilowatt output to a high value by confining the heat output to a short duration electrical peak. That would call for extra storage capacity many times that normally required, the cost of which would absorb any profit obtained from revenue derived from the extra firm kilowatts. It might be noted that the kilowatt rates were based on non-profit-making operation so there was little if any advantage in installing more kilowatts than necessary. It might also be noted that in the case of the Pimlico Scheme the

ample heat storage installed for normal winter operation was utilized in summer to enable the full kilowatt output to be maintained over the period of peak demand for heat and electricity.

Mr Bolton had read Table 8 correctly; each column referred to two schemes each of the same maximum output of heat and electricity and each with the same area and number of consumers served. In the second scheme the total heat and electricity sent out was half that assumed in the first, and a reduction was allowed in the cost of distribution on the assumption that higher maximum pumping losses could be allowed in the second scheme because of the relatively short duration of the peaks of demand.

The information given by Mr Richards on the scheme of district heating installed by the Municipality of Reykijavik was of great interest in showing that, provided a cheap source of heat was available, it could be distributed economically to the public.

Correspondence on the foregoing Paper is closed and no contribution, other than those already received at the Institution, will now be accepted. —SEC. I.C.E.

Paper No. 6000

"Improving the Economics of District Heating"

by

James Frederick Field, B.Sc., M.I.C.E.

(Ordered by the Council to be published with written discussion.)†

SYNOPSIS

The coal shortage and the limited thermal efficiency of the steam turbine-electric generator has turned the attention of engineers once more to the possibility of economic utilization of its waste heat.

The two main difficulties have been the heavy capital cost of distribution, and the effect on the cost of production of the electricity. The Paper is concerned only with the latter effect.

The cost of production of electricity rises partly because the waste heat has to be made available at about 120° F. higher temperature than condenser water. The other main defect is that special back-pressure steam turbines can only be given a yearly load factor of about 50 per cent, even assuming full day-to-day winter storage of hot water.

The latter defect can be avoided by having a double-purpose steam turbine usable as a high-vacuum condensing machine during the winter-day peak-load period, and capable of quick transfer to waste-heat production at about 120° F. higher heat rejection at night. This is possible without prejudice to the highest possible efficiency with either mode of operation.

The Paper also describes an alternative scheme using a modified "gas turbine" steam cycle of much higher thermodynamic efficiency, capable of round-the-year operation without cooling water facilities.

There has been a great deal of controversy regarding the economics of district heating, especially since the national fuel position has become so acute. It can hardly be denied that, other things being equal, the central heating of British homes is desirable for the obvious benefit in standards of comfort, convenience, and public health.

The first question is whether Britain, as a nation, can afford to have district heating on an extensive scale if it is simply an extension of the normal central-heating system with a fuel-fired boiler. The answer is "no"; apart from the capital cost, the fuel will not be available.

The second question is whether it can be afforded if it is combined with electric generation, since the latter requirement for industry is producing ever-increasing quantities of waste heat, and a situation is already approaching in which there will be enough waste heat from this source to keep all

† Correspondence on this Paper should be received at the Institution by the 15th September, 1954, and will be published in Part I of the Proceedings. Contributions should be limited to about 1,200 words.—Sec. I.C.E.

the premises of Britain warm in the winter and to produce domestic hot water as well. The answer here is not a simple one because the commercial side of the question is extremely complicated. It is obvious, however, that the capital cost of distribution of heat, which is a very heavy item in the whole story, can be made bearable where a new housing estate is involved, especially if it consists of blocks of flats as at Pimlico.[1] Alternatively, a thinly populated suburban area must necessarily show a higher capital cost for distribution of the hot water. Existing blocks of flats or tenements could also be converted at costs which would necessarily be somewhat higher, and these would also have to bear the full cost of the radiators within each home, whereas a new scheme could substantially offset the cost of the equipment within the home by the saving on conventional fireplaces and other heating equipment.

The broad issue for or against district heating must be whether, in the long view, it improves the wealth of the nation in the broadest sense. If it could save a really large amount of coal relative to present methods, it could, within a limited total coal availability, enable the nation to produce a great deal more electric power than would otherwise be available, and it seems to be common ground from American experience that increased productivity in the end must depend on the availability of far greater quantities of electric power than are at present available in the United Kingdom. The first question is whether district heating has in fact the prospect of saving extremely large quantities of coal, and if so, whether it is possible to do it at a capital cost which the nation can afford. It might be said on the latter point that if the coal saving is clearly of an exceedingly large order, then the nation cannot afford *not* to do it on a large scale.

In the specific case of Pimlico, there can be no question that the saving of coal as seen by the designers of this scheme, and the saving of coal as seen by the cold dispassionate eye of the electrical-power engineer, will mean two different things. One unit of electricity can, today, be generated for the consumption of less than 1 lb. of relatively poor-quality British coal. With a back-pressure district-heating scheme only 0·4 of the lb. of coal need be charged to the production of electricity, but the saving of coal so far as the electrical-power engineer is concerned is only of the order of less than 0·6 lb. per unit of electricity produced by a district-heating generating-plant. This is where R (the ratio of electric energy sent out to heat energy sent out) becomes pertinent, because the number of such units, and therefore the electrical-power engineer's idea of saving, is directly related to the ratio R. In the case of Pimlico, R is 0·17. In the case of a very large high-pressure high-temperature steam turbine of the most modern conventional type working on a back-pressure cycle, R could be 0·4 or a little better. The saving of coal by the completed Pimlico scheme on this basis could be only about 2,500 tons a year, and it is

[1] See p. 259.

not related to the number of homes efficiently heated, whereas 10,000-tons-a-year saving has been claimed.[2, 3] The additional saving here arises of course, from the fact that the heat is very efficiently utilized by the district-heating method as compared with the average efficiency of conventional heating appliances. This latter figure of coal saving also takes proper account of the number of homes heated. The difference of view, between what might be an electrical-power engineer's opinion based purely on the savings to electric generation and what is really saved because of the more efficient utilization of the heat, is a very important one.

Hitherto the approach seems to have been that a combined electric-generation and district-heating scheme should be owned by one body. Manchester had such a scheme for Wythenshawe, and they proposed to generate electric power by the back-pressure method and to sell that electric power to the British Electricity Authority. Presumably the price offered for that electric power would be of the same order as the cost of production which the Authority experiences with their conventional power stations. It is obvious, however, that a method utilizing special back-pressure sets will suffer because of the poor use-factor to which such sets are necessarily limited, combined with very high overhead charges per kilowatt if any serious attempt is made to obtain a high value for the ratio R. It is possible to store heat at night in storage cylinders, as at Pimlico, for use the following day, but heat cannot be stored in the summer for use in the winter, for obvious reasons; and accordingly the load factor on these back-pressure sets would be poor for the year as a whole, and the capital charges would therefore be very high upon each unit of electricity so produced, in spite of the saving approaching 0·6 lb. of coal per unit of electricity produced, assuming that a fair credit was obtained for the waste heat. There is a special point here regarding the ratio R. It is possible to lower the capital cost of such plant only at the expense of a low value of R. A high R of say 0·4, which would give more than twice the saving of coal of the Pimlico arrangement per therm delivered, would necessitate initial steam conditions of about 1,350 lb. per square inch at 950° F. This problem cannot be solved by using low efficiency plant, because the fall-off in R and in the kilowatt capacity relative to a fixed heating load would be more rapid than the reduction in capital cost; and the national-fuel-conservation part of the objective depends mainly on a high value of R. Or, to put the matter the other way round, the only hope of making a purely back-pressure scheme solvent is to make R very high, so that it could out-perform conventional condensing plant even if there was no sale for the waste heat.

The second fundamental question is the cost to the consumer which can be achieved whilst meeting in a sensible and realistic commercial way all the overhead charges, and assuming that the production cost of electricity

[2] See p. 281.
[3] See reference 4, p. 285.

is not prejudiced; that is to say, that a public electricity authority is not being asked to subsidize district heating from the production of electricity (to do which they would very properly require higher authority). In a recently described hypothetical scheme (see pp. 273 to 281) with a 50-per-cent load factor on the back-pressure turbines (a figure which can be achieved only by winter day-to-day storage on the Pimlico model), it may be noticed that the delivered price per therm drops progressively, as would be expected, with rise in the value of R. Of the total price, there was a fixed charge of £120,000 per annum for the annual distribution of 10 million therms, which is equivalent to an average delivery cost of 2·88*d.* per therm. This means that the cost of production of the heat was of the order of 7·4*d.* per therm with no electric generation, and of the order of 3·4*d.* per therm when the value of R is 0·4. The Author chooses the value of R of 0·4 for this observation because 0·4 can quite easily be achieved with large Rankine-cycle units working at high temperatures and pressures. The reason that the heat production cost is relatively high at a figure of about 3·4*d.*, even at a value of R of 0·4, is simply that the overhead charges on the purely back-pressure generating plant of low use-factor bear unnecessarily heavily on the project.

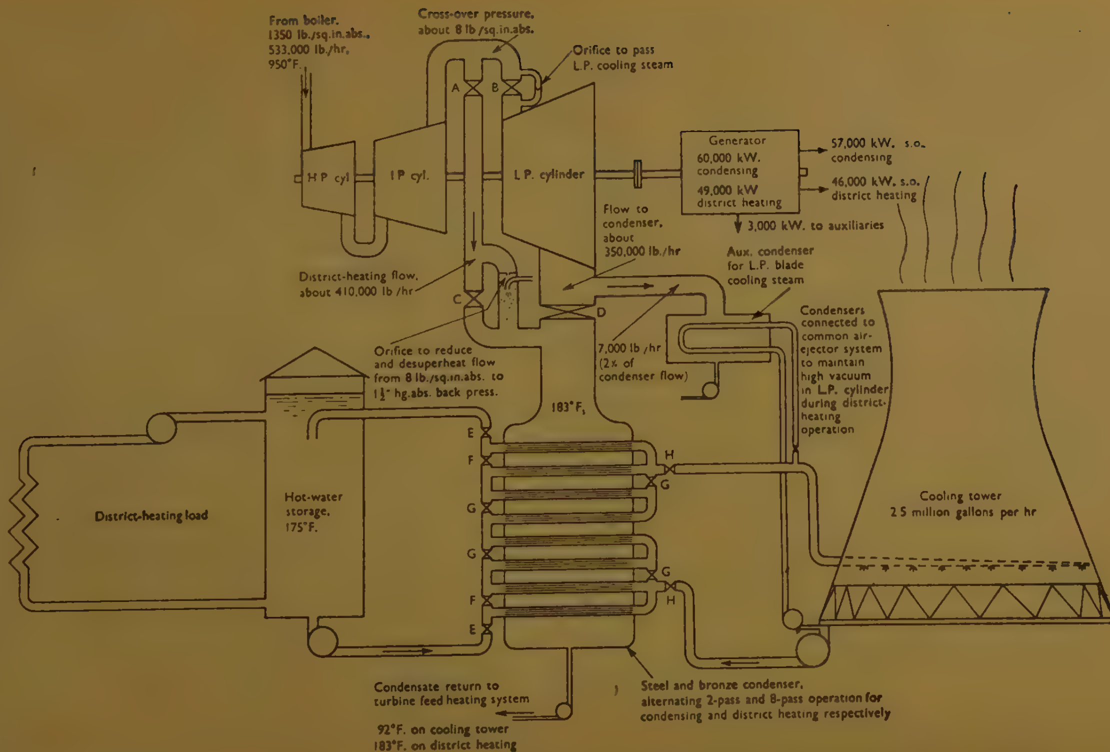
It is possible to get rid of this difficulty by the arrangement shown in *Fig. 1.* It might be described as a "Jekyll and Hyde" turbine, for it can generate at the highest efficiency of which its steam cycle is capable during the 12 hours of a winter day when maximum kilowatt-output is required for the peak load, and can switch over to full production of district heat during the 12 night-hours merely by the operation of a switch which closes and opens a number of valves in a certain sequence. An ordinary automatic pressure-control extraction turbine cannot be made nearly efficient enough for the two separate and distinct conditions of operation.

With normal condensing operation, valves A, C, and E are shut; all other valves are open.

To change over to district-heating operation, valve A is gradually opened, thus by-passing steam from a pressure of 8 lb. per square inch (absolute) through an orifice and desuperheater to condenser. This reduces the load on the set by about 5 megawatts. Valve B is then closed, reducing load on the set by a further 6 megawatts down to about 49 megawatts. The total flow of steam is now passing through an orifice to reduce it to back-pressure of $1\frac{1}{2}$ inch of mercury (absolute) and it is spray-desuperheated to the dry saturated condition. Valve D is then closed to isolate the low-pressure cylinder on an auxiliary condenser for cooling steam only. This is maintained at high vacuum to reduce rotation losses in the low-pressure cylinder to a negligible amount.

The condenser cooling system is then changed over by opening valves E and simultaneously shutting valves F, which puts the main cooling-tower circulating system in parallel with the district-heating system.

Fig. 1



Diagrammatic Arrangement of 60-mW. Set adaptable to Condensing or District Heating without Interruption of Operation

The four valves G are then shut, putting the two systems in parallel on an eight-pass basis for the hot storage water, and with six passes for the main condenser cooling-water, which meanwhile is much reduced in flow because of increased friction head.

Valves H are then shut, leaving the system entirely cooled by hot-water storage.

The degree of desuperheating of the steam is successively controlled during the above valving operations to raise the steam temperature in the condenser shell, valve C being then opened slowly. The inverse timing of these actions will restore the plant to normal condensing operation.

The valves of the condenser system are not of the normal type, but would probably be of multiple-aperture diaphragm type, whereby the movements could be properly synchronized and interlocked to avoid mistakes.

The object of the above arrangement is to save the cost of what amounts to a second full-duty condenser.

Alternatively, where the condenser cooling-water is too dirty to mix with district-heating water, or where it is thought there might be trouble with oxygen in the water, a separate feed heater of large size could be installed some distance from the main set, being connected through a pipe of fairly large but not excessive diameter.

Exclusive of the district-heating mains and hot-water storage, the additional cost of making a 60-megawatt machine suitable for change-over in this manner would be a very small percentage of the capital cost of the complete machine.

As can be ascertained from the figures given in *Fig. 1*, $R = 0{\cdot}393$ in this case, and district-heating production would be at the rate of 4,020 therms per hour. The cost of the heat has virtually no overhead charges in its make-up since it is now generated off peak; it need only bear the cost of the loss of electricity production as between condensing and district-heating (that is higher-back-pressure) operation. The figure actually works out at 1·07*d.* per therm at the power-station end (see Appendix 1), and can be looked upon as a heat-pumping charge for raising heat which is available free of charge at 80–90° F. at the condenser, to the required 175° F. The act of operating the turbine at a higher back pressure is, of course, thermodynamically equivalent to the use of a perfect heat-pump of 100 per cent efficiency. (This is why it is wrong to pump waste heat from thermal generating stations, as has been seriously suggested on a number of occasions.) Incidentally the original cost of the coal is equivalent to 3·4*d.* per therm, so that the cost of the waste heat pumped to 175° F. is only 32 per cent of this, and it is in a form where it can be utilized for house heating with almost 100 per cent efficiency. It is incomparably cheaper than any alternative form of low-temperature heat, but it requires a very expensive distribution system to make it available in the home. Since the 60,000 kilowatts would operate district

heating for only half of the 24 hours, it would serve a population of about $\frac{2{,}010}{455} \times 11{,}000$ = say 50,000 people, and would save at least 50,000 tons of coal a year on the basis of argument used relative to Pimlico.

With the above possibilities, the issue is clearly reduced to a question of distribution cost, and in concentrated areas such as that considered in the hypothetical scheme described on pp. 273 to 281, there appears to be an overwhelming case in favour of district heating, even for existing buildings where the cost of radiators and other expenses would have to be added.

There are parts of Britain selected for new towns and housing estates which are nowhere near a capital power station, and indeed the great majority of existing villages and small towns now do not have any large power plant close to them, since all the stations most recently constructed have had to consider the question of cooling water for their usually very-large-size units, above anything else.

For this situation the only hope of a really economical scheme in terms of cost to the consumer (and worthwhile also in the long view for national coal conservation) is the development of a relatively small generating plant capable of a considerably higher value of R than is possible with a conventional steam turbine. To keep the cost of heat down, apart from the cost of distribution within such a small scheme, it would be necessary for such power plant to be capable of running with as good a load factor as any condensing-power-station plant; and it follows that however carefully the capacity of such a plant was balanced with the district-heating load, and even assuming adequate day-to-day heat storage in the Pimlico pattern, it would still be necessary to reject a good deal of the waste heat in the summer months by deliberately throwing it away to the atmosphere as in conventional practice. *Fig. 2* and Appendix 2 indicate what is now possible in this direction. The capacity of the plant indicated is 15,000 kilowatts, whereof 14,673 kilowatts can be sent out to the electricity mains, whilst a heat output of 850 therms per hour is available. R is exactly 0·59. In the winter, such a plant could run 24 hours a day, and on the basis of Pimlico's aggregate turbine output of slightly more than half that quantity of heat, this installation could serve a community of about 20,000 people. None of the hot water need be wasted in the cold winter months, but as the summer came on it would be necessary to get rid of the heat if the turbines were to be kept in use, as is essential to economical overhead charges of electricity production. The hot-water-storage cylinders, of which there would be two or three of the Pimlico size for this unit, are therefore also adaptable as cooling towers, by removing the insulation from the surface of the actual storage cylinder and attaching this to the inside of the architectural screen surrounding the tower. Cooling surfaces of suitable configuration are then attached to the hot-water-storage cylinder after the manner of the cooling surfaces attached to an electric transformer, and in fact the conditions on the air side are bound

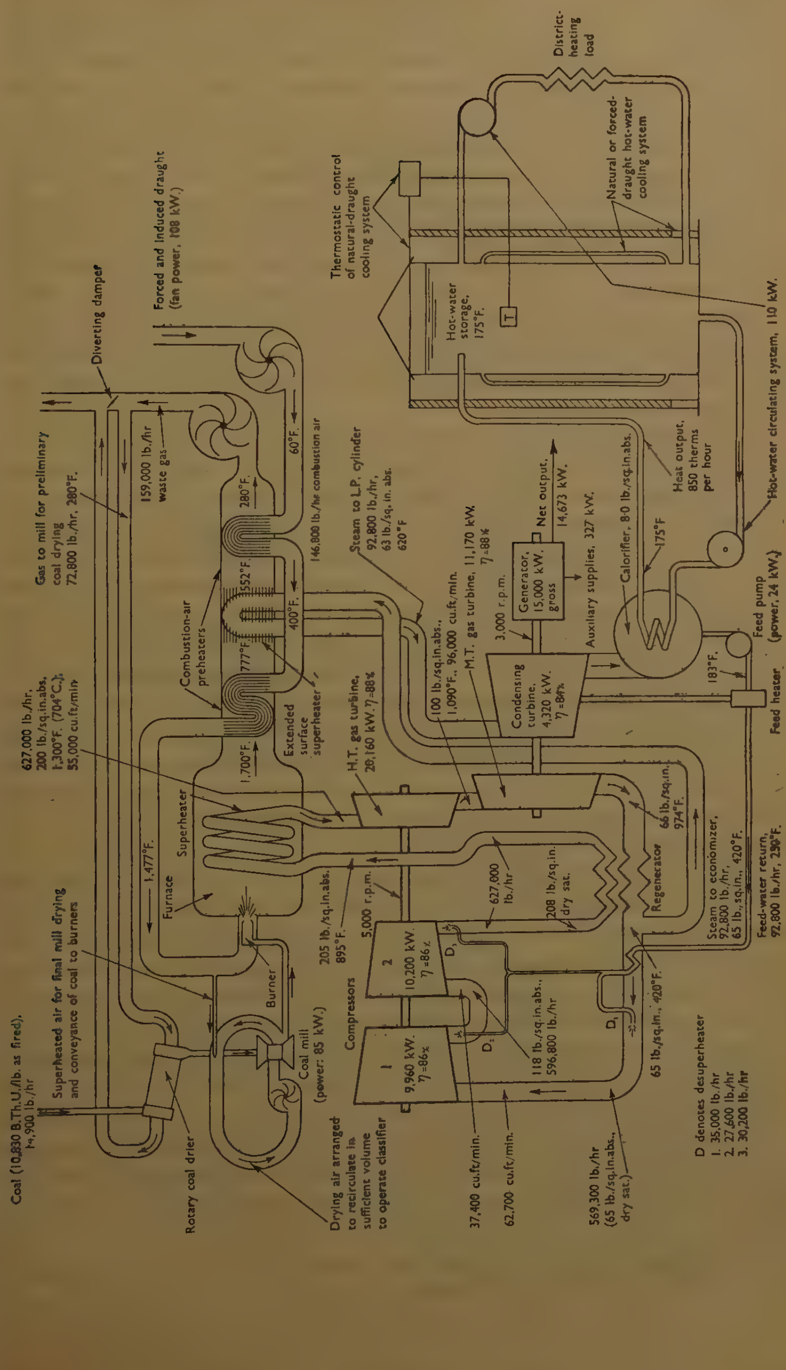

Coal (10,830 B.Th.U./lb. as fired), 14,900 lb./hr
Superheated air for final mill drying and conveyance of coal to burners
Rotary coal drier
Drying air arranged to recirculate in sufficient volume to operate classifier
Coal mill (power: 85 kW.)
Burner
Furnace
1,477°F.
Superheater
627,000 lb./hr, 200 lb./sq.in.abs., 1,300°F. (704°C.), 35,000 cu.ft./min
Gas to mill for preliminary coal drying 72,800 lb./hr, 280°F.
Diverting damper
159,000 lb./hr waste gas
Forced and induced draught (fan power, 108 kW.)
Combustion-air preheaters
1,700°F.
777°F.
552°F.
280°F.
60°F.
400°F.
146,800 lb./hr combustion air
Extended surface superheater
H.T. gas turbine, 20,160 kW. η=88%
205 lb./sq.in.abs. 895°F.
5,000 r.p.m.
Compressors
1
9,960 kW. η=86%
2
10,200 kW. η=86%
D₁
D₂
D₃
37,400 cu.ft./min.
62,700 cu.ft./min.
569,300 lb./hr (65 lb./sq.in.abs., dry sat.)
118 lb./sq.in.abs., 596,800 lb./hr
627,000 lb./hr
208 lb./sq.in. dry sat.
65 lb./sq.in., 420°F.
Regenerator
66 lb./sq.in. 974°F.
100 lb./sq.in.abs., 1,090°F., 96,000 cu.ft./min.
M.T. gas turbine, 11,170 kW. η=88%
Steam to L.P. cylinder 92,800 lb./hr, 63 lb./sq. in. abs. 620°F
Condensing turbine, 4,320 kW. η=84%
3,000 r.p.m.
Generator, 15,000 kW. gross
Net output, 14,673 kW.
Auxiliary supplies, 327 kW.
Calorifier, 8·0 lb./sq.in.abs.
175°F
183°F.
Feed heater
Feed pump (power, 24 kW.)
Steam to economizer, 92,800 lb./hr, 65 lb./sq.in., 420°F.
Feed-water return, 92,800 lb./hr, 230°F.
D denotes desuperheater
1. 35,000 lb./hr
2. 27,600 lb./hr
3. 30,200 lb./hr
Heat output, 850 therms per hour
Hot-water circulating system, 110 kW.
Hot-water storage, 175°F.
T
Thermostatic control of natural-draught cooling system
Natural or forced-draught hot-water cooling system
District-heating load

Fig. 2

to be very similar because the temperature rise between water and air is of much the same order as that experienced between oil and air in electric transformers. A considerable amount of heat can be dispersed by a thermostatic natural-draught chimney device as shown, and a great deal more (more than twice as much) can be rejected by applying only a moderate amount of forced draught to the bottom of the tower, as in certain types of more conventional cooling towers. There is no question that this particular kind of dry-air cooling tower would be considerably less objectionable in a built-up area than the conventional vapour type. The total amount of heat rejected by these cooling towers would be nothing like as great as that from an equivalent capacity of conventional plant. Their duties would be virtually zero for the 3 winter months of the year, and they would only have to reject a substantial amount of waste heat in the summer months when the night electricity-load for the nation as a whole would be very low.

This plant is designed to work on a steam cycle more akin to that of a gas turbine than a steam turbine, and a full description of this cycle has appeared elsewhere.[4] The so-called "gas turbine" components are identical in construction with conventional gas-turbine components, except that the blading has a somewhat different configuration to suit the lighter medium (steam). The inlet operating temperature of about 1,300° F. is associated with the exceedingly low pressure for steam machinery of 200 lb. per square inch. The pressure could be half this figure, the only difference being to make the gas-turbine machinery slightly more bulky. Gas turbines are already being built for inlet temperatures of 750° C. (= 1,382° F.) for a life of 100,000 hours minimum. This long life is achieved by judicious cooling of the high-temperature components. The efficiencies noted on the diagram are conservative for gas-turbine components, and it is probable that such a machine would have a slightly better performance than that indicated.

All the engineering difficulties associated with this type of engine have already been solved in other applications. The most interesting in many respects is the superheater. Here it is necessary to achieve the high steam-temperature with a pressure-drop which is low relative to conventional plant. This is achieved by controlling the volume of combustion associated with a given amount of heating surface, and it has resulted in the need for the combustion chamber to be divided into a number of separate cells of comparatively narrow long cylindrical shape. The superheater tubes would be of Nimonic 80A, which can be operated continuously at 800° C. (metal temperature) for a life of about 100,000 hours, provided the stress is kept below 1,000 lb. per square inch. With a 1-inch tube of $\frac{1}{8}$-inch wall thickness the stress would be about 800 lb. per square inch. It is essential

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[4] J. F. Field, "The Application of Gas-Turbine Technique to Steam Power," Proc. Instn Mech. Engrs, vol. 162 (1950), p. 209.

in a superheater of this kind to use a parallel-flow arrangement as between combustion gas and steam, and to maintain the whole of the superheater active surface as nearly as possible at the limiting temperature, irrespective of the temperature of the steam inside the tube. Accordingly, where the radiation effect from the flame is greatest it is necessary to speed up the steam within the tube, so that the rate of forced convection inside the tube is related to the radiation flux outside the tube in such a manner that a steady temperature of 800° C. is maintained along the tube. This is a relatively straightforward problem and involves only a certain amount of cut-and-try in the amount of obturation effect required at the back of the tube.

It may be noted that for electricity production alone, ignoring the usefulness of the waste heat for district heating purposes, the plant can have a " sent out " efficiency of 31·1 per cent which is practically as good as the best Rankine-cycle large-size steam turbine now operating in Britain (Portobello No. 1). On condensing operation to a vacuum of say 29 inches of mercury, this kind of plant would have " sent out " an efficiency of at least 38 per cent with the component efficiencies stated. The circulating-water-pump energy would be considerably less than that shown for district heating. It is well known that present gas-turbine-component efficiencies can probably be considerably improved, so that 40 per cent thermal efficiency " sent out " under condensing conditions should be comparatively easily achieved without exceeding 1,300° F. at 200 lb. per square inch absolute.

To reach a value of $R = 1{\cdot}0$, it will probably be necessary to raise the inlet temperature to 900° C. and drop the pressure to say 100 lb. per square inch. This is clearly a possibility for gas turbines and for a low-pressure superheater.

Under the district-heating conditions shown, R, as already stated, works out at 0·59, but the total cost of district heating by this method will be considerably less than that shown on the hypothetical scheme described on pp. 273 to 281, because of the great improvement in use-factor made possible by turning the hot-water-storage tower into a combined cooling tower for the summer months. The economics of the scheme would be somewhat more attractive still if it could switch over to condensing operation with a high vacuum in the summer and during the day period of the winter months, as suggested in relation to *Fig. 1*, and in fact this could easily be arranged near a river if normal cooling-water facilities were available ; but in a great many residential areas in Britain these facilities will not be available, and the scheme as outlined will have the advantage that it is a completely air-cooled scheme and could go almost anywhere in Britain without prejudice to amenity. In particular, a considerable number of these small units could be distributed in carefully chosen sites over a large city, and could be base-loaded summer and winter alike, to

keep the whole community warm and to give them the electricity that their industry requires.

It is interesting to speculate that on the Pimlico heat-consumption basis probably 40 million people out of the 52 million in the United Kingdom could be served by 2,000 of these sets (having a total capacity of 30,000 megawatts). The coal saving would be of the order of at least 50 million tons per annum, and is probably the only way of being sure that another 30,000 megawatts can be added to the national generating capacity. The cost of the generating plant alone would be very little more than that of conventional generating plant, since the large number of small sets desirable with such an approach would ensure the ability to produce them in batches of say one hundred at a time. Modern control techniques already available would enable units of this type to be remote-controlled in any particular city from a central control room. In the Author's view, for British conditions, the large condensing power station in its present form is already outmoded by the stern reality of the fuel problem.

The Paper is accompanied by three sheets of diagrams from which the figures in the text have been prepared, and by the following two Appendices.

APPENDIX 1

Assumed steam conditions for normal condensing operation :—

Supply pressure : 1,350 lb. per square inch gauge
Supply temperature : 950° F.
Feed heat : + 450° F.
Vacuum to cooling tower : 28½ inches mercury (average)

Condensing net output of set : say 60 mW. – 3 mW. = 57 mW.
With same steam flow exhausting to 8 lb. per square inch absolute :—

Output = 49 mW. – 3 mW. = 46 mW.

Assuming that exactly 1 lb. of coal (of calorific value 11,000 B.Th.U. per lb.) produces 1 kilowatt-hour of "sent-out" electricity (condensing operation) then :—

Production = 2,240 kWh. per ton of coal, costing, say, 70*s*. or 840*d*.

Heat added in boiler	= 1,035·1 B.Th.U. per lb.
Coal calorific value at 57 mW. sent-out	= 57,000 lb. × 11,000
	= 627 × 10⁶ B.Th.U. per hr
Heat value at stop valve	= 88% of 627 × 10⁶
	= 552 × 10⁶ B.Th.U. per hr
Therefore throttle flow	$= \dfrac{552 \times 10^6}{1{,}035 \cdot 1}$
	= 533,000 lb. per hr
District heating operation gives $2{,}240 \times \frac{46}{57}$	= 1,810 kWh. for 1 ton of coal, costing 840*d*.
Equivalent fuel loss	= 430 lb. per ton of coal burned, worth 161*d*.
Heat output of boiler	= 57,000 × 11,000 × 0·88
	= 552 × 10⁶ B.Th.U. per hr

Heat for electric power (district heating) $= \frac{100}{98} \times 49{,}000 \times 3{,}413$
$= 171 \times 10^6$ B.Th.U. per hr

" District Heat " available $= (552 - 171) \times 10^6$ B.Th.U. per hr
$= 381 \times 10^6$ B.Th.U. per hr

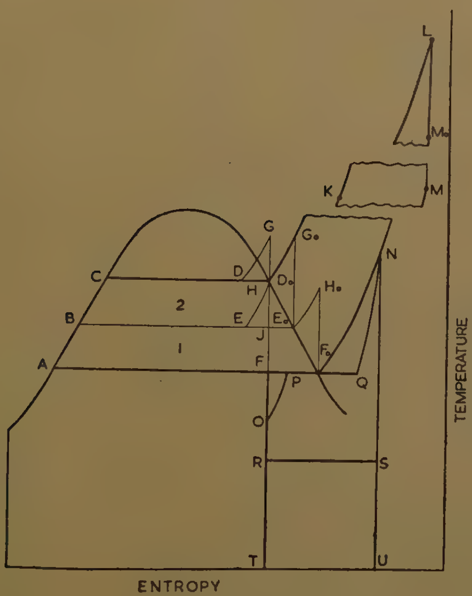
" District Heat " available per ton of coal burned $= \frac{381 \times 10^6 \times 2{,}240}{57{,}000}$
$= 15{\cdot}0 \times 10^6$ B.Th.U. per hr
$= 150{\cdot}0$ therms per hr

at a cost of 161*d.* = 1·07*d.* per therm

Original coal cost

$$\frac{840d.}{2{,}240 \times 11{,}000} = 3{\cdot}41d. \text{ per therm}$$

Fig. 3



Household coal cost: about 5·0*d.* per therm
Efficiency of use of household coal: say 20 per cent
Effective cost of heat from household coal: say 25*d.* per therm
Efficiency of transmission and use of district heat: about 95 per cent
Therefore effective delivered cost of district heat (exclusive of transmission capital costs and incremental overhead charges on domestic installation)
= 1·13*d.* per therm

Appendix 2

15,000 kW. District-Heating Turbine Based on "Field" Cycle
(1,300° F. inlet temp. (704° C.) 8·0 lb. per sq. in. abs. back pressure)

(*Computation based on dry compression using Keenan & Keyes* 1936 *steam tables*)

	Point on entropy diagram (*Fig. 3*)	Pressure : lb. per sq. in. abs.	Temperature : ° F.	Entropy	Total heat : B.Th.U. per lb.	Adiabatic heat drop : B.Th.U. per lb.	Casing efficiency : per cent	Water fraction added : per cent	Steam fraction compressed : per cent	Mechanical heat at shaft : B.Th.U. per lb.
Compressors (1 lb. of steam at high-pressure outlet after desuperheating) 1.	N F_0 HH_0 (a)	65·0 ,, 118·0	420 Dry sat.	 1·6374 ,,	1242·9 1179·1 1230·4	— 51·3	86·0	5·6	90·8	— 54·2
2.	HH_0 EE_0 GG_0 (a)	,, ,, 208·0	426 Dry sat.	 1·5891 ,,	1238·7 1190·1 1240·1	— 50·0	86·0	4·4	95·2	— 55·4
	GG_0 DD_0	,, ,,	466 Dry sat.		1248·3 1198·9			4·8		
								Regenerative heat : B.Th.U. per lb.	External heat added : B.Th.U. per lb.	
High temperature turbines and regenerator (1 lb. of steam) 1.	D_0 K L M_0 (a)	208·0 205·0 200·0 100·0	Dry sat. 895 1,300	 1·9404 ,,	1198·90 1473·75 1688·15 1563·55	+ 124·6	88·0	+ 274·85	214·4	+ 109·6
2.	M_0 M (a) M N	100·0 66·0 66·0 65·0	1,090 974 420	1·9500 ,,	1578·55 1509·40 1517·75 1242·90	+ 69·15	88·0	— 274·85		+ 60·8

Condensing turbine with economizer

	Point on diagram	Pressure : lb. per sq. in. abs.	Temperature : ° F.	Entropy	Total heat : B.Th.U. per lb.	Adiabatic heat drop : B.Th.U. per lb.	Casing efficiency : per cent.	External heat added : B.Th.U. per lb.	Steam fraction expanded : per cent.	Mechanical heat at shaft : B.Th.U. per lb.
Condensing turbine (0·148 lb. of steam) (200° F. superheat added in " economizer " = 98·5 B.Th.U. per lb.)	N SR	63·0 8·0	620 183	1·8197 "	1341·4	$188{\cdot}9^{5}$	$84{\cdot}0^{5}$	98·5	14·8	+ 23·5
	O		250	0·3675	218·5					
										+ 84·3

Condensing turbine ideal regenerative cycle[5] heat drop $= (1341{\cdot}4 - 218{\cdot}5) - 643\,(1{\cdot}8197 - 0{\cdot}3675)$
$= 1122{\cdot}9 - 934{\cdot}0 = 188{\cdot}9$ B.Th.U.s/lb.

Condensing turbine output per lb. of " gas turbine " flow $= \dfrac{188{\cdot}9 \times 84{\cdot}0 \times 14{\cdot}8}{100 \times 100} = 23{\cdot}5$ B.Th.U.s

Engine efficiency (including " economizer ")

$$= \frac{84{\cdot}3}{214{\cdot}4 + (98{\cdot}5 \times 0{\cdot}148)} = \frac{84{\cdot}3}{228{\cdot}97} = 36{\cdot}8 \text{ per cent}$$

Plant efficiency (excluding auxiliaries)

$$= 36{\cdot}8 \times 0{\cdot}89 \times 0{\cdot}97 = 31{\cdot}8 \text{ per cent}$$

Net plant efficiency

$$= 31{\cdot}8 \times \frac{14{,}685}{15{,}000} = \underline{31{\cdot}1 \text{ per cent sent out}}$$

Weight of steam circulating in high temperature turbines $= \dfrac{15{,}000 \times 100 \times 3{,}413}{97{\cdot}0 \times 84{\cdot}3} = 627{,}000$ lb. per hour

Weight of steam bled off at N $= 627{,}000 \times 0{\cdot}148 = 92{,}800$ lb. per hour

Heat output $= \dfrac{627{,}000 \times 214{\cdot}4 \times (100 - 36{\cdot}8)}{10^7} = 850$ therms per hour

Electricity output $= 14{,}673$ kW.

$$\text{Ratio } R = \frac{14{,}673 \times 3413}{850 \times 10^5} = \underline{0{\cdot}59}$$

[5] J. F. Field, " A Suggested Basis of Comparison for the Efficiency of Steam Turbo-Generators and of Steam-Electric Generating Stations." J. Instn Civ. Engrs, vol. 10, p. 241 (Dec. 1938).

ORDINARY MEETING

19 January, 1954

WILFRID PHILIP SHEPHERD-BARRON, M.C., T.D., President, in the Chair

The Council reported that they had recently transferred to the class of

Members

Cooper, Guthrie Stewart, B.Sc. (*Glasgow*).
de Morsier, Theodore Edward, B.Sc. (Eng.) (*London*).
Fraenkel, Peter Maurice, B.Sc.(Eng.) (*London*).
Grigson, Reginald Ronald West, T.D., B.Sc.(Eng.) (*London*), (*former Member of Council*).
Nixon, Marshall, M.B.E., T.D., B.Sc. (*Durham*).
O'Connor, Patrick Ibar, B.E. (*National*).
Oliver, Malcolm Campbell.
Samuely, Felix James, B.Sc.(Eng.) (*London*).
Sanderson, Henry Fenton.
Shaw, Thomas Wareing, B.Sc. (*London*).
Smith, Reginald Henry Trivess.
Webber, Arthur Charles.

and had admitted as

Graduates

Airton, James Robert, B.Sc.(Eng.) (*London*), Stud.I.C.E.
Allardyce, William Frank Gray, B.Sc. (*Aberdeen*).
Barlow, Edward Haggas, B.Sc.Tech. (*Manchester*), Stud.I.C.E.
Barron, Ross, B.Sc. (*Nottingham*).
Bartholomew, Philip, B.Sc. (*Leeds*).
Base, Geoffrey Donald, B.Sc.(Eng.) (*London*).
Beales, Derek Peter Bradfield.
Berry, Derek Wilfred, Stud.I.C.E.
Bradley, Roger Edward Allen, B.Sc. (*Birmingham*).
Brittain, Patrick Bernard.
Broadbent, Earle George, B.Sc. (*Glasgow*), Stud.I.C.E.
Brown, Charles Dargie, B.Sc. (*St. Andrews*).
Brown, Harry Templeton, Stud.I.C.E.
Brown, Kenneth John, B.Sc.(Eng.) (*London*).
Bruseth, Nils, B.Eng. (*Liverpool*), Stud. I.C.E.
Cairncross, Arthur Alexander, B.Sc. (*St. Andrews*).
Cameron, Archibald Wilson, Stud. I.C.E.
Candlish, Thomas Tait, B.Sc. (*Glasgow*).
Carter, Alan Reginald.
Charlton, Brian John, Stud.I.C.E.
Claridge, Peter James, B.Sc.(Eng.) (*London*).
Clark, John Martin, Stud.I.C.E.
Clarke, Brendon, B.Sc. (*Belfast*).
Cook, William Macfarlane, B.Sc. (*Glasgow*).
Corden, Joseph, B.Eng. (*Liverpool*).
Corlett, Malcolm Campbell, B.Eng. (*Liverpool*).
Court, Christopher David, B.Sc.(Eng.) (*London*), Stud.I.C.E.
Dailey, Robert James, B.Sc.(Eng.) (*London*).
Davis, John Albert, B.Sc.(Eng.) *London*), Stud.I.C.E.
Duff, Alan, Stud.I.C.E.
Dundas, George Alexander, B.Sc. (*Durham*).
Eames, Robert George, B.A. (*Cantab.*).
Edwards, John Whitford, B.Sc.(Eng.) (*London*).
Egleston, James Fergus, B.E. (*National*).

Ellston, Benjamin, B.Sc. (*Manchester*), Stud.I.C.E.
Farrar, Richard Edmund Scruton, B.Sc.Tech. (*Manchester*), Stud.I.C.E.
Fernando, Merennege-Ratnapala, B.Sc.(Eng.) (*London*).
Flower, Brian Langfield.
Fraser, James Douglas, Stud.I.C.E.
French, Donald William, B.Sc.(Eng.) (*London*), Stud.I.C.E.
Glanfield, Roy William John, Stud. I.C.E.
Goodearl, Kenneth Arthur, B.Sc. (Eng.) (*London*).
Gordon, James Lawrie, B.Sc. (*Aberdeen*), Stud.I.C.E.
Gorton, Frank Anthony, Stud.I.C.E.
Grant, Edward, B.Sc. (*Aberdeen*).
Griffin John Stanford, B.A. (*Cantab.*).
Gunasekera, Chandrapala, B.Sc. (Eng.) (*London*), Stud.I.C.E.
Hamley, Elwyn William, B.Sc.(Eng.) (*London*), Stud.I.C.E.
Hanby, John Hancock.
Harvey, Brian Norman, Stud.I.C.E.
Harvey, Joseph Thomas, B.Sc.(Eng.) (*London*).
Hawes, Leonard Dennis, B.Sc.(Eng.) (*London*), Stud.I.C.E.
Heeley, John Mark, B.Sc.(Eng.) (*London*).
Henbest, Reginald James, Stud.I.C.E.
Humby, Eric James, BSc.(Eng.) (*London*).
Jackson, Kenneth Raven, B.Eng. (*Sheffield*).
Jayasinghe, John Stanley, B.Sc.(Eng.) (*London*), Stud.I.C.E.
Jeyaweerasingam, Somasundaram, B.Sc.(Eng.) (*London*), Stud.I.C.E.
Jones, Edward Malcolm, B.Sc. (*Wales*).
Kathirgamathamby, Kandiah, B.Sc. (Eng.) (*London*).
Kelsey, Ronald William Robert, B.Sc. (Eng.) (*London*).
Kemp, Victor James Arthur, Stud. I.C.E.
King, Denys Michael Gwilym, B.Sc. (Eng.) (*London*) Stud.I.C.E.
Kirk, Alexander Laurence, B.Sc. (*Edinburgh*).
Knight, William Alexander, B.Sc. (Eng.) (*London*).
Kopec, Andrew Richard, Stud.I.C.E.
Kotagama, Neville Jayampathy Bandaranayake, B.Sc.(Eng.) (*London*), Stud.I.C.E.
Lambert, Lincoln Arthur, B.Sc. (*Leeds*).
Lawrence, John Englefield, Stud. I.C.E.
Lennon, Michael Thomas.
Lewis, Brian William, B.Sc.(Eng.) (*London*), Stud.I.C.E.
Lown, Kenneth David, B.Eng. (*Liverpool*).
McDonnell, Robert, B.E. (*National*).
McHenry, Frederick Harold, B.Sc. (*Belfast*), Stud.I.C.E.
McKenna, John Michael, B.Sc.(Eng.) (*London*), Stud.I.C.E.
MacKenzie, Donald Francis Peter, B.A., B.A.I. (*Dublin*).
McMullan, John Gerard, B.Sc. (*Belfast*).
Maitland-Carter, John Ernest, B.E. (*W. Australia*).
Marshall, John Mackay Campbell, B.Sc. (*Glasgow*), Stud.I.C.E.
Mead, Ronald James, B.Sc.(Eng.) (*London*).
Mortimer, David Hugh Propert, B.Sc. (Eng.) (*London*).
Moss, Ernest Geoffrey, Stud.I.C.E.
Moss-Morris, Arthur Louis, B.Sc. (*Witwatersrand*), Stud.I.C.E.
Munn, Harvey, B.Sc. (*Glasgow*).
Munro, Donald, B.Sc. (*Glasgow*).
Murphie, Robert Kenneth Douglas, B.Sc. (*Glasgow*), Stud.I.C.E.
Nelken, Ludwig, B.Sc.(Eng.) (*London*).
Nutt, Richard David, B.A. (*Cantab.*), Stud.I.C.E.
Palmer, Roger Aylwin, B.E. (*New Zealand*), Stud.I.C.E.
Parsons, Peter John, B.Sc.(Eng.) (*London*), Stud.I.C.E.
Paterson, Walter Sutter, Stud.I.C.E.
Pegge, Edward Vernon, B.Sc.(Eng.) (*London*).
Percy, John Henderson, B.E. (*New Zealand*), Stud.I.C.E.
Prickett, Robert James, B.E. (*New Zealand*).
Rajendra, Ponniah, B.Sc.(Eng.) (*London*).
Rees, Malcolm, B.Sc.(Eng.) (*London*), Stud.I.C.E.
Reynolds, John Michael, B.A. (*Cantab.*).
Richardson, Gilbert, Stud.I.C.E.
Richardson, John, B.Sc.(Eng.) (*London*), Stud.I.C.E.
Roberts, Reginald George, Stud. I.C.E.
Robson, Rex Thomas, Stud.I.C.E.
Schofield, Reginald Bryan, B.A. (*Cantab.*).
Scott, Kerry Owen, B.Sc. (*Aberdeen*), Stud.I.C.E.
Scrace, Roy John William.
Sellers, Jack.
Sethna, Aspi Rustom.
Simpson, John, B.Sc. (*Glasgow*).

Somasundaram, Devaraja Eliyatamby.
Song, Peter, B.Sc. (*Hong Kong*).
Stephenson, Herbert Douglas, B.Sc. (*Durham*), Stud.I.C.E.
Stevens, Kenneth William.
Stewart, Joseph, B.Sc. (*Belfast*), Stud. I.C.E.
Temple, Ronald Arthur, B.Sc.(Eng.) (*London*), Stud.I.C.E.
Thornton, Edward Peter, B.Sc. (*Belfast*).
Timmins, John Bradford, Stud.I.C.E.
Tolbutt, Alan John, B.Sc. (*Cape Town*).
Tollick, Francis Campbell, B.Sc. (*Edinburgh*), Stud.I.C.E.
Tunbridge, Alan Dawes, B.Sc.(Eng.) (*London*), Stud.I.C.E.
Tunstall, Robin Harold, Stud.I.C.E.
Tymms, Robert Samuel, B.Sc.(Eng.) (*London*), Stud.I.C.E.
Waters, John George, B.Sc. (*Leeds*).
Weerakoon, Chandradasa, B.Sc.(Eng.). (*London*).
Wells, Alan Paul, B.Sc.Tech. (*Manchester*).
Weston, Roy Francis, B.Sc.(Eng.) (*London*), Stud.I.C.E.
Whalley, James Douglas, Stud.I.C.E.
White, Kenneth Francis, B.Sc.(Eng.) (*London*), Stud.I.C.E.
Whiteley, Desmond, B.Sc.(Eng.) (*London*).
Wilson, David Gordon, B.A. (*Cantab.*), Stud.I.C.E.
Wilson, Fred, B.Sc.(Eng.) (*London*).
Winfield, Brian Herbert, B.Eng. (*Liverpool*).
Winship, Richard Frederick.
Winter, George Brian, B.Sc. (*Birmingham*).
Young, Thomas Leslie, B.A., B.A.I. (*Dublin*).

and had admitted as

Students

Backhouse, Peter Frederick.
Banerji, Biswanath.
Barritt, Patrick John.
Best, Michael Treloar.
Bill, James Ingram.
Bogle, James Main Lindam Linton.
Bowie, Ian George.
Boylan, James.
Bracegirdle, Ronald Bernard.
Bridges, Brian Crawford.
Bullock, David Thurlwell.
Buttress, Donald James.
Buxton, Lawrence Alan.
Calverley, Michael Anthony Alton.
Cantrell, Philip Alfred.
Carr, David Robert.
Carter, John Michael.
Chan Boon Teik.
Chan Hean Loon.
Cherry, John Michael Stephenson.
Chodri, Makhan Lal.
Clark, Derek James.
Clegg, John Hodgkinson.
Coates, Bernard Roy.
Collett, Geoffrey John.
Cotterell, Stephen John.
Cowie, Francis Lawson.
Doshi, Jagdishchandra Jagjiwandas.
Downey, Eric.
Duncan, Andrew.
Edwards, Brinley John.
Evans, Peter Bennett.
Fernando, Camillus Hilary.
Fleming, Wilfred George Kenneth.
Forrest, Donald Mitchell.
Fraser, Alexander Fernie.
Ganguly, Rasbihari.
Garton, Alan.
Griffith, John Arthur Wilkinson.
Grundy, Norman Lewis.
Harkness, David Thomas.
Harper, Thomas Neil.
Harries, Dewi.
Harris, David Howard.
Harrison, Frederick.
Hay, William Plenderleith.
Haynes, Frank Keith Beaumont.
Healey, Michael Grayson.
Hennessy, Desmond Joseph.
Henry, Walter James.
Hirst, John David.
Hiscock, Keith William.
Hollands, Sidney Albert.
Idiens, Ivan John.
Jackson, Peter.
Jenkins, John.
John, Alan Percival.
Johns, Michael Charles Bedford.
Jones, David Pennant Graham.
Keith, David Stevenson.
Khan, Mahamad Sadik.
Kilpatrick, Hugh James.
Kin, Ryszard.
Lawrence, John Douglas.
Ledwidge, Michael Denis.
Lickrich, John.
Lindsey, Norman Edward.
Low, Desmond George.

Ludgate, William Graham.
Lusty, John Frederick.
McArthur, John.
McCracken, Victor Hugo.
Macdonald, Ian Charles Burrington.
McGrath, Frederick James.
McKay, Paul Minchin.
MacLuskie, Iain Baird.
Marsh, John Brian.
Marshall, William John.
Mazda, Shahrokh Rustom.
Meller, Roy Edward.
Mochrie, Alistair Herbert.
Moon, Michael Roy.
Moore, Harry.
Nadarajah, Arumugam.
Newhouse, Christopher Kenneth.
Onabanjo, Samuel Folorunso.
Padmore, Michael Stualt.
Palmer, Dennis.
Panchalingam, Appiah.
Parmar, Shamsher Singh.
Peeke, Bruce Richard.
Pelzer, Klaus Friedrich.
Penny, Joseph Herbert.
Peters, Robert Victor Lawrence.
Phillips, William Freer Coles.
Poole, David Gerard.
Poppy, Donald Lorenzo.
Rashid, Abdul.
Rawe, Joel.
Reader, David.
Rennie, Brian David.
Roach, Michael James.
Roberts, David Brian.
Satgunasingam, Kumarasingam.
Scott, William Gilbert.
Sharples, Gordon.
Sheikh, Mohammad Islam.
Sim, James.
Skyrme, Bryan Beaumont.
Smith, Robert Swan.
Smith, Thomas Graham Wright Colquhoun.
Sood, Romesh Kumar.
Spillard, Benjamin Charles.
Suttie, Kenneth.
Sutton, John Philip.
Tanner, David Brian.
Thorp, Terence Norman.
Trotter, Gordon Tarrant.
Turnbull, Edward Donald.
Turnbull, William Brown.
Turrill, Arthur Derek.
Vestey, Peter James.
Volrath, Peter Geoffrey.
Waters, Anthony George.
Watson, David Malcolm.
Watson, John.
Whigham, George Robertson.
White, Keith Christopher.
Wilde, Peter Malcolm.
Williams, Alec Henry.
Williams, Henry Browne.
Williamson, David.
Wilson, Antony William.
Wintrip, Roy.
Wood, Raymond John.
Woolmore, Derek Clive.
Yaqub, Mohammad.

The following Paper was presented for discussion and, on the motion of the President, the thanks of the Institution were accorded to the Author.

Paper No. 5984

"The Engineer Task in Future Wars" *

by

Major-General George Newsam Tuck, C.B., O.B.E.

SYNOPSIS

Any future war will be profoundly influenced by new scientific discoveries and their engineer application.

Military success may depend on skilful adaptation of novel engineering methods to tactical or strategic aims.

A vital contributory factor is peacetime collaboration between the Royal Engineers and civil engineers in engineer planning, organization and the solution of military problems by the latest technical developments.

In the land and tactical air force battle, defence works may demand more machinery and prefabrication. New types of land obstacles are also needed.

In equipment and assault bridging, mainly a military interest, vast improvements have recently been made. Civil bridges will require classification and strengthening.

Problems of airfield construction are complicated by operation of heavier jet aircraft. Soil stabilization and new surfaces suggest possible solutions.

Other vital tasks include: fuel pipelines, "across the beach" delivery, rapid repair and construction of roads and railways, accommodation, field workshops, field tools, power supply, lighting, project illumination and stores handling.

Military plant and equipment should, where possible, correspond to standard civilian practice. Often some specifically military feature enhances the commercial value of a machine, especially for export to undeveloped countries.

This Paper deals with those tasks which fall to the Royal Engineers in war. They include not only construction and destruction, but also range over the whole field of civil, electrical, and mechanical engineering, including transportation and survey. They do not include signals, vehicle repair, motor transport, electronics, or armaments.

In seeking to define the subject of this Paper the attention of the Author was drawn to the meaning of the word "engineer." In his opinion the dictionary definition fails to convey the popular or the technical meaning of the word as it is used today, and the Author suggests that the engineering Institutions should take action to have included the notion of "one who studies a profession."

It is necessary to draw some distinction between engineering in peace and engineering in war. The conception of engineer work in peace is of something completed and fulfilling a definite utilitarian purpose; examples range from a Sydney Bridge or an Aswan Dam to a jet engine. Through the range of pictures conjured up in the mind two factors predominate

which are not entirely fulfilled in war-time engineering: first, a tidy job completed in every detail of the designer's conception; secondly, a clear-cut specification of functional requirement. Perhaps a third factor should be included, though not always achieved in peace; it is that of a work adding to man's heritage of aesthetically beautiful possessions.

War is governed by the principles of war—the soldier's creed, sacrosanct and immutable. These principles concern equally the Royal Engineer and the infantryman. It often falls to the engineer to lead the way in offensive action. In offence and defence, destruction is an important engineer task. Engineering is vital to mobility in both the battle-area and in movement forward from base. The time factor in war has an over-riding priority which is not experienced in civil engineering. Surprise, economy of force, and the uncertainty commonly known as the "fog of war," frequently present the engineer with an ill-defined requirement to be met with inadequate resources and with every chance that the governing conditions will change during the execution of the work.

These reflexions must be related to the march of science. The motto of the pure scientist and of the research engineer at the present time is like that of the Red Queen's "Faster, faster." In peace, applications can be fully tested before the introduction of a new technique into practice. In preparation for war, the engineer must be ahead of the enemy in application. The advance of science is so rapid and new discoveries so revolutionary that it is not easy for the soldier without technical knowledge to be up to date in the method of waging war. The professional engineer, in collaboration with the scientist and the research engineer, has opportunities to recommend how new methods can be evolved by applying new techniques.

From these general considerations the Author suggests two tentative conclusions:—

(1) That the approach of the engineer to future war problems should not be "I will wait until the Military state a firm requirement and then I will study the job." The engineer should, in the Author's opinion, venture to say "From my study of the military problem, I find this application of modern engineering would contribute to its solution. I consider the engineer task should be framed accordingly and that the military plan should conform." Maybe that is going too far, but should not engineers risk an advanced position initially, although it may subsequently be convenient to withdraw some little distance? Professionally, are they not too inclined to wait for other people to tell them what should be done? This attitude may be the right one in peace-time civil life (although it is not suggested that it is), because professionally qualified engineers hold a sufficient proportion of influential appointments in government, in Parliament, in the Civil Service, and

on boards of directors. But in time of war, and in planning for war, surely the profession will be doing the country a disservice if it does not throw the full weight of its knowledge, skill, experience, and imagination into deterring the aggressor by the application of superior technical skill in warfare.

(2) That Clausewitz's theory of the whole nation at war is applicable, while a world is suffering from ideologies, to "cold war" as well as to a future major war. The aim is to win the "cold war" to prevent a "hot war." "Cold war" seems to resolve itself into minor shooting campaigns in the less developed parts of the world and into developing a firm military front to give security in more civilized countries. The civilian and the soldier are involved together in the "cold war" all the time—politically, economically, and militarily. Every individual civil engineer would be called out for the nation's defence in a "hot war," indeed, in a sense, all engineers are unpaid Royal Engineer reserve officers. Engineers also have opportunities to contribute their services during the "cold war," for example, the Public Works Department are already busy in Malaya and Kenya.

This Institution is actively assisting both engineer planning for future war and the technical training of Royal Engineer officers. To quote one of the Past-Presidents, Sir William Halcrow, who wrote the foreword to the symposium of sixty-eight Papers published by the Institution[1] after the 1939–45 war.

> ". . . the war gave rise to many novel engineering problems, and to the exercise of considerable ingenuity in their solution. . . . The Papers give evidence of the close collaboration that existed between the regular and temporary members of the Services, and it is to be hoped that this collaboration will continue no less strongly in times of peace."

The first part of this Paper has dealt with the mental approach of civil engineers in peace-time to their tasks in a future war. Since it is the spiritual concentration of force which wins battles, it is the Author's belief that the engineer contribution to defence in a future war depends primarily on the interest taken by the profession in military problems during peace-time. The initiative of this Institution, by encouraging its members to study military engineering, is inspiring to the Royal Engineers and of great service to the Army.

The second part of the Paper attempts to forecast some of the practical problems of a future war, but first it is well to mention and dispose of a complication. It is traditional in the Corps of Royal Engineers that they pioneer any new thing. Mechanized road transport began with steam

[1] "The Civil Engineer in War," Instn Civ. Engrs, 1948.

tractors in South Africa, and aircraft, tanks, signals, and bomb-disposal are a few examples pioneered by the Corps. There will be new things to pioneer, possibly things with only a tenuous connexion with engineering as such. Appropriate civilians will find themselves wearing the Sapper badge, whether as pressed men or volunteers, to pioneer novelties. The Corps are no longer responsible for the novelty once it has emerged from the experimental stage into a new commitment, otherwise it would distract the Corps from its proper task of engineering. The civil engineer has, in war and peace, his share in this pioneering task of the Royal Engineers.

Turning then to engineer tasks in a future major war. The first step must be to imagine what a modern "hot war" will be like. Looking back, there seem to be only three things common to recent wars: first, someone else starts it; secondly, during the first year Britain hangs on grimly; and thirdly, she wins the military contest in the end. A fourth could be added: that modern wars are too big to handle without allies—and to quote Field Marshal Sir William Slim, "When thinking about our allies, it's wise to remember that we are an ally ourselves."

The lesson learnt from history is that in any other respect the next war will be very different from the last, but a fair assumption is that it will start by enemy aggression, with superior forces on the ground and in the air, and a considerable nuisance value at sea. These are important assumptions to the engineer, because the first phase will pose major engineer tasks before the Country is mobilized and organized for war production.

It can be accepted that major war aggression will never stem from democracies or from a United Nations organization. Aggression will be by a dictator, who must aim to exploit surprise and the initiative to gain quick results, otherwise the rest of the world will have time to rally against him. If this is right, ruthless committal of the full weight of armed forces to gain the maximum success from the initiative must be anticipated.

It seems vain to hope that mankind will not be so mad as to release the forces of scientifically developed "mass destruction." And if this disaster happens, it must be assumed that the aggressor possesses plenty of atom bombs, aircraft, and guided missiles, for without a full armoury he dare not attack. The newest known factors in aggression are the destructive power of atom war-heads against concentrated targets, the greatly increased range of delivery, and the greatly increased speed and range of guided or piloted air-missiles.

Sir Winston Churchill has said that land-war will become a broken-backed affair because the attack on communications will paralyse supply systems. In the Author's opinion the difficulty of maintaining logistic movement will present engineers with one of their biggest problems. This problem will be considered by examining a campaign in a highly developed area, say Europe, and by confining the argument to the engineer tasks overseas.

In such a campaign the first concern of the engineer is to assess the

existing civilian resources of transportation, communications, engineers, and labour. In addition there will be some strategic airfields, magazines, communications, etc., prepared in peace-time.

It will be the enemy's aim to demoralize the civilians and destroy the means of movement of supplies and reinforcements. His atom weapons are most effective against concentrated targets such as cities and ports, and he has at his disposal high-explosive weapons which can be delivered at long ranges to tackle smaller targets. He may also be able to organize sabotage.

In the battle-area, in the air and on land, modern air forces and armies require delivery of much greater tonnages of fuel, ammunition, and almost everything else, than were provided for them in the last contest. It is important at this point to remember that superior numbers can be withstood only by superior technique and superior fighting equipment. The cost per piece of equipment, aircraft for example, is becoming astronomical. Active defence forces maintained in peace will tend to be very good, rather small (because nations cannot afford large forces), but very precious. Everything will depend on keeping them amply provided logistically from the very start so that their superior quality can achieve maximum results.

Broadly speaking, the answer to weapons which destroy concentrations is to disperse the resources under attack, but the dispersion must not become too expensive in manpower, communications, and overheads. Military problems will of course centre on certain commodities, such as fuel, because the civilian lay-out of reserves and distribution will have little relation to military requirements, either in protection or in end-location of delivery. The Army will be equally concerned with centres of communication, such as ports, where stores are transferred from one form of transport to another or which present vulnerable sea or land defiles. In particular the human element, skilled and unskilled labour, is physically and morally very vulnerable to attack by mass-destruction weapons.

There will be, in fact, all the known engineer problems of the 1939–45 war, multiplied several times in magnitude, and of these, transportation remains one of the major problems. Because of the scale of destruction, new solutions to logistic problems must be found.

The lesson learnt from history is that, broadly speaking, the engineer solution to providing the means of movement from base to battle has been to develop existing civil resources to meet military requirements. In the last European campaign it proved to be quicker and more economic to repair airfields than to make new ones. This was unexpected, for air-photographs of the French, Belgian, and Dutch airfields, continuously attacked by Allied heavy bombers and abandoned by the Luftwaffe, showed overlapping craters filled with water. To all appearance, drainage systems had been wrecked beyond repair and there was no possible way of siting

a new runway without first filling a large number of craters. Reconnaissance on the ground of the first airfields recaptured, at Evreux and St André, indicated that repairs sufficient to provide minimum facilities for forward fighter wings were not so formidable a task as had appeared from the air-photographs. The truth is that destruction generally looks more frightful than it really is. A permanent Dutch airfield can be quoted as a typical example, where access roads, aircraft standings, and a surprising percentage of the original facilities were found to be intact. The main drainage system, as was usual, was damaged rather than destroyed. The whole airfield area had originally been properly drained, consolidated, and formed, so there was no need to fear the soft spot which was very often a delaying factor in making a virgin-earth strip. There were other factors not fully appreciated until St André was repaired. Local labour employed by the Germans on the airfields was quickly traced and re-employed. Airfield plant was found locally—often it had been dismantled and hidden by the "underground." Plenty of hangar rubble was handily placed for filling craters. In Holland and Belgium bricks and pavé from parts of the airfield that were not required could be taken up and relaid by local tradesmen skilled in the work.

The Author has described repair of airfields in 1944 at some length because the example illustrates several basic lessons of the 1939–45 war which may well apply in the future.

The first of these lessons is that a well constructed utility, particularly if it is designed in peace-time with a view to war-time requirements, can often be kept in action or repaired to meet military requirements. The best examples are the German strategic railways and the autobahnen, where strategic requirements were over-ruling factors in both lay-out and design. The narrow canal-bordered roads of southern Holland, on the other hand, were not suitable for modern military traffic. This is a point on which civil-engineer influence can be brought to bear in peace-time, even where construction is not specified to cater for war requirements. Indeed it may not be a question of extra expense in the original construction, but only of forethought in design. It is an aspect of peace-time construction that should be kept in mind in the United Kingdom, in the Commonwealth, and wherever British engineers undertake construction for allies.

Restoration of utilities after large-scale destruction entails a major commitment in clearing a way through the debris to uncover the objective for repair. With atom weapons this process is complicated by contamination, particularly contaminated dust. Two examples, from the 1939–45 war, serve to illustrate this type of problem.

During the battle of the bridgehead in Normandy, heavy bombers were let loose on German centres of communication. When No. 30 Corps broke out of the bridgehead southwards, the engineers under the Author's command had to make a route through two small towns, Aunay and Pont de Conde. The tanks and forward infantry had bypassed the towns but the

Corps could not advance farther through these two towns without roads capable of carrying at least 3-ton lorries, and the time factor was of the order of 24 hours. Examination by air from an Auster aircraft failed to discover even the alignment of the original roads ; in fact, these two towns were just a heap of rubble. There was no way round ; it was impossible to go through, because there was neither the gear nor the time to shift tons of rubble, and there was no space into which to bulldoze it to one side. The solution had to be a rough lorry-track right over the top. This example was the result of a heavy bomber raid on poorly constructed old country villages, and perhaps it serves to help the imagination to assess the effect of atom bombs on a city.

The second example is from the first months of re-occupation of the Ruhr and deals with opening a canal for coal barges. In a stretch of about 10 miles, more than a hundred heavy steel-girder bridges had collapsed into this canal. Among them were many railway bridges, one long clear-span autobahn bridge, and several main road bridges, with lengths ranging up to 1,500 yards and spans often up to 300 feet. The destruction in this instance was almost entirely caused by enemy demolition ; it is, however, the kind of girder clearance task which is to be expected from atomic weapons.

Nevertheless, it is the Author's opinion that it will very often be quicker to repair than to build something new. The technique of clearance and repair is therefore an important study in relation to future war. The Author suggests that one possible way of producing results quickly, in spite of mass destruction, may lie in the mass employment of machines. Indeed, in war, many kinds of rapid new construction, in particular those entailing earth-moving, demand a military engineer plan based on the deployment of plant in quantity, for example, new airfields and roads. The practice is common in certain types of civil works, such as earth dams, except that the time factor is perhaps not so critical. Where the machines and skilled operators are to come from, and how to get them overseas if they were available in the United Kingdom, is an interesting planning problem. Furthermore, it is not easy to give Royal Engineer officers in peace-time the knowledge or the proper experience of war-time technique.

From the foregoing examples two points stand out ; first, the autobahn conception or the strategic railway conception, so well executed by the German Wehrmacht in both world wars, were civil utilities laid out to be easily adapted to war needs ; and secondly, the application of massed plant to deal with mass destruction. It is believed that civil engineers in peace-time can contribute something to both of these war-time problems.

Engineers should be encouraged to think out the logistic problem *ab initio*. The requirement is to deliver commodities, without delay or stoppage, from the United Kingdom arsenal to the user overseas. The present logistic system relies on holding buffer-stocks up the line of communication, using bulk delivery part of the way and breaking down

commodities at stock-holding points for detail delivery to the user. Is this the best solution, given modern engineer facilities? Suppose that freighter aircraft on a daily supply round from the United Kingdom to division could deliver everything needed. The problems of maintenance areas and of dispersion would then be of minor importance. Of course this suggestion is not practicable in face of enemy air-power, but it serves to illustrate how speed of transportation and through-delivery without transhipment can help to solve such problems. The modern PLUTO across the Channel, expanding into a gridded piped system overseas, was a solution based on the same principles. With cranes and fork-lifts designed for cross-country movement, heavy packages could be handled at the receiving end, however far forward it might be. Safe carriage and ease of break-down from bulk to item may be improved by advances in methods of parcelling and packaging. Long-distance belt conveyors might be adapted to solve movement without transfer of loads or manhandling. It may be possible to deliver electric power by grid to forward areas or to install mobile power stations in forward areas; the Services today have far too many small power plants for every little workshop, headquarter, and depot, each requiring its delivery of fuel. These few possibilities are mentioned only to stimulate ideas and illustrate the problem.

In considering solutions it is important to remember that in this selected example the overseas theatre is thickly populated. Allies may well need military engineer assistance to keep their civil utility services functioning. Their civil utilities will equally be required to allocate resources for military purposes. The military engineer problem must never be divorced from the civilian problem. Indeed, one of the essential components of the solution must be an inter-allied organization to allot resources and decide priorities; and the organization must have the authority to do these things across territory belonging to several allies. Local manufacture to save transportation from the home-base must also be considered.

The next problem is: "What is happening to the enemy?" His logistics will certainly be suffering severely, and his difficulties must be examined. Sad as it may be for the ally who is closest to the aggressor; the hard fact must be accepted that against modern weapons it may not be possible to halt the superior air and ground forces of an aggressor at the frontier. Of course an aggressor can be hit at long range, but his momentum will carry him so far. In this event, while offering tenacious resistance, it would be possible to create in the path of the enemy a transportation desert in order to slow his advance. The Germans did this effectively in their 1917 strategic withdrawal, but of course they had time to do a methodical and painstakingly thorough job. Even in limited time, and in face of rapid advance, it is suggested that engineers today, 35 years later, equipped with modern machines and power, could rip the bottom out of every airfield, road, railway, bridge, and bridle path, and sow mines in the

resulting debris. The enemy cannot fight without forward airfields or without means of transport for fuel and ammunition. Certainly hardy troops could live on the country for a while, but even Napoleon's Revolutionaries were halted by the desolation east of the lines of Torres Vedras. Behind such a belt of scorched earth the defending tactical air forces should be able to regain air superiority, and the land forces should have time to reinforce and to organize offensive counterthrusts. It is doubtful if there is opportunity to practise the technique of destruction in civil life, but the subject presents interesting engineering problems.

Some aspects of defence in battle must be considered. There are two modern theories of " start of war " tactics. One is great mobility with armour, wide dispersion (hence no atom targets), and much manœuvre. The other is a defensive strategy after a first withdrawal, to gain time for the air force to win the air battle and to prepare for offensive action while manœuvring astride a broad obstacle which armour cannot penetrate without deliberate assault. Whichever turns out to be the answer, quickly made defences are still needed, either to provide secure bastions round which to manœuvre, or to protect the defenders behind the obstacle. Manual digging and hand-made overhead cover are effective, but slow and fatiguing. Prefabrication, the use of machines, the mechanical handling of stores to site, the mechanical laying of mines, and many other improvements are in sight and give scope for application in future wars. Of course there are equally important engineer assault problems in breaching gaps through defences, minefields, and obstacles.

To construct effective obstacles economically is another " battle " problem. There is a requirement to save mines by covering a greater frontage per mine and to make the whole process of mining more mobile. A further requirement is to find a substitute for barbed-wire. Farmers now use simple electric fences, but although electric fences have been used by the Army in the field, no satisfactory military solution has yet been found. Barbed-wire is certainly effective, but it is difficult to handle, heavy, and objectionable in almost every characteristic. The 1939–45 war saw no development progress in this type of defence equipment and improvement is overdue.

It is not intended to expand the many ways in which engineering can contribute to the " sharp end " of the land battle. Broadly speaking, the effectiveness of the engineer effort depends on increasing mobility and speed of execution, in reducing the weight and bulk of material, and in doing more with fewer men. One of the tools needed is some form of mobile cross-country machine combining the attributes of tractor, fork-lift, and excavator, which will save manpower and time, and will get there under its own power at convoy speed without a trailer or transporter.

In one Paper it is not possible to discuss every engineer responsibility, but there are two specific tasks which demand detailed examination, namely, bridging and airfields.

Assault floating-bridges are the Sappers' own particular problem without exact parallel in civil life. It can be claimed that in equipment bridging, British military designs are ahead of those of any other country. Modern developments have made possible the assembly of floating-bridges well back from the river bank, and from this point assembled components are taken forward and launched into the river direct from trailer. If conditions are difficult, monorails or sledges are used. Simplicity and speed of assembly can be achieved on good ground and under cover where cranes, dim lights at night, and other facilities are available. No vulnerable targets are presented on the river bank and men have no heavy weights to handle from the bank or while afloat. Power tugs are employed for rafting bridge sections into position. When the loadings stipulated for modern armies are taken into account, this is a remarkable achievement, and it is believed that this technique will be the pattern for future wars. Further advances in the technique of assault bridging will depend on the solution of tactical problems arising from the vulnerability of bridges to long-range missiles and on the time factor in the requirement for heavy armour on the far bank.

For clear-span bridging there is now a new design of heavy-girder Bailey-type bridge. This has been erected and launched off flat firm ground by one man with a fork-lift truck. This is not the normal procedure, of course, and it entails remote control of levers by wire attachments, but it serves to illustrate the simplicity of design and the manageable size and shape of components. The Army uses equipment bridges for a number of reasons; first, for speed of erection; secondly, because in war there is seldom time to collect and prepare local materials or alternatively there are no materials available; thirdly, to ensure delivery to bridge site, often by bad roads or tracks; fourthly, for ease of erection by field engineers without the assistance of tradesmen or tools; fifthly, for flexibility in span and loading; and lastly, so that when a bridge has served its purpose it can be dismantled and re-erected. Some of these factors do not apply to engineer projects in peace, but some of them may often condition the approach-bridging problems of large works in undeveloped countries, and possibly there is a latent demand for equipment bridging in civil life.

Bridging requirements include the very quickly made short-span bridge, a need now met by the tank bridge-layer, and the short-span sectional-truss railway bridge. In addition, a future war requirement is foreseen for strengthening existing bridges. The inspection and classification of existing bridges is in itself quite a problem. Investigations have shown how far bridges fall short of modern load requirements and particularly of Army requirements. Even in the United Kingdom, bridges are a bottleneck; surprisingly enough many of the bridges on main roads cannot carry heavy military transport loadings. Our present solutions include a design for a sectional prestressed-concrete girder suited to a wide range of

requirements and the compilation of Tables and data to assist engineer units in employing local continental resources which are, of course, based on metre gauge.

In connexion with Army equipment generally, it is obviously desirable for the Army to use standard commercial patterns rather than to have special designs. Special designs entail tooling-up of production lines and the holding of war-stocks including spare parts. This is a Ministry of Supply rather than a War Office responsibility, but naturally it is very much to the advantage of Royal Engineers to use standard articles. It is believed that developments to meet specific military requirements often produce results which it is commercially profitable to apply both to home and export markets. When this happens, every encouragement is given to civil engineering firms to market the particular line. Nevertheless, the Author believes more can yet be achieved, both by the Royal Engineers, in closely watching new civilian products to see whether they fulfil adequately enough the military requirement, and by civil engineers in designing equipment suitable for modification for military use.

The airfield requirement has changed considerably since the 1939–45 war. This Paper mainly deals with its most difficult angle—the hasty airfield. Today the engineer is faced with single-wheel loads of 20,000 lb. and tire pressures of 300 lb. per square inch. The runways must have jet resistance, be proof against fuel spillage, and be dustproof.

There are of course several lines of approach, for example, stabilization, stabilization combined with a metal track surfacing, or untreated soil with a prefabricated surfacing. It is not proposed to go into the progress of development but mention must be made of some general problems. Special surfacing not used in civil life needs war reserves; also, with the length of modern runways and the requirement for protective dispersion, the coverage area will involve huge tonnages. If material is to be saved by stabilization, a battery of mixing machines is needed to compete with the time factor of completion; also detailed and scientific reconnaissance is necessary to obtain accurate knowledge of site conditions. Thus the problem of the hasty tactical airfield is a difficult one.

In civilized countries there is every prospect of a steady increase in the number of civil airports. Trends in aircraft must surely be towards both increased range and increased speed. In the Author's opinion air transport will be used for both passengers and freight in war. The prospects then for the airfield engineer in war-time are the maintenance of existing military air bases, the adaptation of civil airports for military operational or transport aircraft, the hasty construction of airstrips for the tactical air forces or as satellite fields, and the construction in undeveloped countries of both semi-permanent and hasty airfields. The probability is that airfield construction will absorb a far higher proportion of engineer effort in a future war than it has done in the past. There are two main facets to the problem of development and design: the semi-

permanent airfield constructed with maximum economy in time and material; and the hasty airfield. The uncertainties perhaps lie even more in aircraft development than in changes in strategic plan. If the aircraft designer can bring a fast heavy aircraft to earth slowly and softly, the engineer can resuscitate the earth strip and the metal surfacing of the 1939–45 war. However, the present forecast must anticipate strong surfaces stretching long distances.

To show that the many other engineer tasks are not forgotten, a paragraph is devoted to miscellaneous items; they are included in this category, not because they are unimportant in quantity of effort or quality of technique, but because there is no space to enlarge on every problem. First, there are roads: an interesting problem is how to protect a secondary road very quickly, as the first division moves forward over it, so that the surface, bottoming, and drainage are not severely damaged before the engineers have opportunity to repair the pot-holes. Further problems include:—

- Railway construction, destruction, repair, and railway operation, including locomotive design.
- Field workshop machinery and power supply, and field-unit tools.
- Generating sets, lighting, and both battlefield and project illumination.
- Port construction, operation, and maintenance across beaches.
- Fuel supply, including flexible cross-country pipe-lines, ship-to-shore pipe-lines, pumps and both temporary and semi-permanent rapidly installed tankage.
- Water-supply.
- Accommodation, in which interesting problems of dispersion and protection arise from threat of air or long range missile attack.
- Bomb disposal, which must now include the possibility of an atom bomb failing to explode, entailing new techniques in reconnaissance and disposal.

In considering a future war, the military engineer is forced to apply to every problem the limitations and flexibility imposed by geography and by climate. The lesson of major wars is that each successive war spreads farther around the world than the last. Engineer designs, organization, planning, and equipment have to cater for cold, heat, drought, and humidity. The Author suggests that great circle routes, the shortest way from point to point, may well attract attention to the polar regions. Engineers may be faced with projects on the perma frost, and in arctic regions which can be reached only by air or by a sea route open for but one or two months during the year. Polar travel and polar experiment is being developed rapidly and it seems probable that polar routes will come into everyday use in peace, and may need extension in war. Thus, the problems and techniques of arctic transportation and construction are

likely tasks for engineers in a future war. Lastly, the extension of possible theatres of war to new territories creates work for the Survey directorate which is already fully committed to mapping new areas. Survey problems concern not only unmapped territory, but also new degrees of accuracy devolving from progress in electronic methods of survey, and the need to provide data for long-range missiles. It may not be accurate enough to know that the Atlantic bulges upwards about 50 metres, and that Europe is also on a bulge, while India is in a depression about 60 metres deep. Geodesy and space measurement are likely to present new problems of survey in a future war.

In this Paper it has not been possible to do more than to indicate in the most general terms the broad nature of engineer tasks in a future war. Indeed, special problems have been neglected to the extent of omitting reference to campaigns in forests, deserts, and mountains. The Author has made certain forecasts and assumptions based on known weapons and on a war in the air, on land, and at sea, bearing some resemblance to recent experiences of warfare. So rapid is the progress of scientific discovery that new weapons and new methods of warfare are very likely to evolve within the next decade. It is rash to venture any opinion of future trends; nevertheless it would be unwise to expect any diminution in the magnitude of the tasks of the engineer. Indeed it is on this theme that this Paper should be concluded. Whatever the precise nature of engineer tasks in a future war, it seems inevitable that their urgency, their scope, and their magnitude will impose a very severe test on the whole engineer resources of the Country, on its engineering skill, on its engineer manpower, on its equipment, and on its production. Security in war may depend as much on the success in mobilizing and deploying engineer resources as on any other single factor. It is therefore with gratitude that the Royal Engineers welcome the valuable collaboration of the Institution of Civil Engineers in holding a meeting such as this in order to discuss future military engineering problems.

Discussion

Mr R. M. Wynne-Edwards said that perhaps the most useful contribution the civil engineer could make to the military engineer might be in the training of the Sapper officer. The Author was hoping that the civil engineer who was fully conversant with a continuously up-to-date knowledge of civil engineering practice, would apply his mind to military problems in peace time. Mr Wynne-Edwards did not think that that was likely to be very productive because the civil engineer, as the Author had described, was busy fulfilling very utilitarian civil purposes. He was not paid to think about military matters; he was paid to do civil things.

Perhaps the best contribution which civil engineering could make would be to help the Army (whose daily job was to be conversant with military problems) by making available to the military engineer information about all the latest civil engineering practice; but only the Army could ensure that that information was assimilated and the Sapper officer hoping for promotion would be required to be just as *au fait* with design or construction techniques as his opposite number in the civilian world must be, who was ambitious to advance in his profession. It was indeed absolutely vital for the military engineer to acquire that knowledge somehow.

Any war would obviously present a number of new problems, and no doubt if it went on long enough new devices would be designed and manufactured to cope with some of them; but when war broke out the Sapper had to make the best use of existing plant and techniques, because they and the civilian engineers who knew how to use them were the only resources he had immediately to hand. As a rider to that, of course, the Army had to know exactly where to find those resources.

One could well believe that all that was more easily said than done. Some members might remember that in a discussion many years ago at the Institution a Sapper officer had said that the Sapper started off with a very good academic grounding, but by the time he was thirty he found that it was more important to keep his Company accounts right than it was to know about engineering. That was a real problem which had to be faced in the Army, and it was only the Army who could solve it.

The long course was obviously a very good start and he wondered whether the idea was used to its limit. For example Singapore and other ports were busy mechanizing their cargo handling; he wondered whether Sapper officers were collaborating in those studies or learning from them. Again Sapper officers ought to take a great deal of trouble to discover how contractors maintained the efficiency of their equipment.

He felt quite certain that the civil engineering profession and industry would be pleased to help the Army in every way by bringing Sappers in touch with what was going on. If the Army could ensure that its knowledge was sufficiently up-to-date to know how to make use of that which was available, it would have gone a long way to solving all the problems that could be satisfactorily solved in peace time.

Brigadier C. E. A. Browning said that as Commandant of the School of Military Engineering he was intimately concerned, under the Engineer-in-Chief, with the training of the young regular Royal Engineer officer. National Service officers, who also attended the School, were expected to complete their training as civil engineers in the profession after their National Service.

It was quite obvious that the young regular subaltern had to be ready and trained to undertake a very wide range of tasks in war. He had to do the job which was in front of his nose at the critical time and place, and

he had to be prepared to take on tasks at very short notice and frequently work from first principles. There was no doubt that the War Office's policy that he should be trained on broad lines was right. The curriculum had to be sound and in accordance with professional standards and experience; it should include sound teaching of the application, operation, and maintenance of earth-moving equipment—quite a big task in present times.

The young regular Royal Engineer officer broadly speaking received 5 years' training initially in his profession, and it was conveniently broken up into four phases. The first phase was the 18-month period which he spent with the Royal Military Academy at Sandhurst where, in addition to receiving his basic military training, he also received academic training designed to fit him to take Part I of the Joint Paper, and for those officers educationally capable of doing so, to be ready to pass the Cambridge University qualifying examination for the Mechanical Science Tripos. On leaving Sandhurst, after 18 months, he went to the School of Military Engineering at Chatham for 4 months. That was his first training after receiving Her Majesty's Commission. Those 4 months were spent mainly on field engineering and tactics. The subjects included fixed and floating "equipment" bridges, field works and field defences generally, demolitions, and mine warfare. There was also some regimental training, tactics, and man-management. That involved 4 months of hard work. Then the young regular officer, before proceeding to phase 3, was sent over to Germany to the British Army of the Rhine where he served 2 months with a field engineer regiment, in order to give him practical experience of the job on manœuvres. After phase 3 he would either proceed to Cambridge University, where he took a 2-year mechanical science Tripos course, or to the Royal Military College of Science. There he took the 3-year B.Sc. engineering course, London University External, or a 2-year general science degree. In addition the Royal Military College of Science had started an advanced 2-year diploma course, which, with some adjustments on the teaching of civil engineering subjects, and, taken in conjunction with the training at the School of Military Engineering, might lead to exemption from Parts I and II of the examination for Associate Membership of the Institution. That was not yet quite firm on the military side, but everything was working satisfactorily in that direction and it was the firm policy of the Engineer-in-Chief.

Phase four began when the young officer had completed his 2 or 3 years at Cambridge University or at the Royal Military College of Science. He then came back to the School of Military Engineering at Chatham for 48 weeks for continuation training in civil engineering, electrical, and mechanical subjects. There he was given practice in the application of those engineering theories which he had learned at the Universities, with particular reference to their military engineering application. The subjects covered were: the design and construction of timber, steel, and

reinforced-concrete structures; electrical generation, transmission, and distribution; plant operation and application; the construction of roads and airfields; building and workshop practice; and engineering survey. It was a fairly large field to cover but it simply had to be covered if the young Sapper officer was to have a sufficiently flexible mind to take on the task facing his Corps in war.

At the end of the 48 weeks' period he took an examination which consisted of a series of 3-hour papers and several practical projects. The Sappers present at the meeting would remember the old "F" project in pre-war days; they were similar projects in a more up-to-date form. It was hoped that that examination, monitored by the Institution, would be accepted as giving exemption from Parts I and II of the Institution's examination for Associate Membership. Those young officers who had achieved honours degrees were already exempt.

At the end of that period the young officer went out into the field engineer regiments of the Corps, the Engineer-in-Chief's policy being that the young officer should go to regiments, mostly overseas in Germany, the Middle East, or the Far East, for practical experience as a troop commander in the Royal Engineers. He would probably remain there until reaching the rank of captain.

Sometime between the ages of twenty-seven and thirty-two (depending on his availability), the slightly more senior engineer officer came back to the School of Military Engineering for the long engineering course. Those courses had been mentioned by Mr Wynne-Edwards and they were undoubtedly of great value. They lasted for just over 2 years and were divided into three phases. The first phase of 7 months was spent in the civil, electrical, and mechanical engineering departments of the School of Military Engineering; engineering theory and practice were again studied, in retrospect, so as to make quite sure that the young officer had not forgotten what he had been taught in the past and to bring him up-to-date. At the end of 7 months he joined (with the generous co-operation of the profession) a firm as a junior executive engineer for 11 months, in order to gain practical experience and understanding of the civil side of the profession. At the end of that period he spent a further 7 months attached to a consulting engineer where he had to learn as much as possible of the planning of large projects. It was invaluable experience and at the end of that time he was in a position to write his thesis. Then if he were fortunate, and had sufficient ability, he obtained Associate Membership of the Institution of Civil Engineers or of some other professional Institution.

It might be added that it was the Engineer-in-Chief's policy to send on that course only those officers who had already achieved exemption from Parts I and II of the professional examination.

Of about 1,600 serving regular officers, 530 (or 32 per cent) had obtained an honours degree at Cambridge University or the B.Sc.(Eng.) at London

University. Thirty-five officers (2·2 per cent) were either Members or Associate Members of the Institution. Twenty-five officers (1·5 per cent) were Members or Associate Members of the Institution of Mechanical Engineers; and twenty-two officers (a little more than 1 per cent) were either Members or Associate Members of the Institution of Electrical Engineers. So that eighty-three regular officers in the Corps (5 per cent) were either Members or Associate Members of professional Institutions, the majority being Members or Associate Members of the Institution of Civil Engineers.

Mr P. St. L. Lloyd said that the Author had quite properly taken as his underlying theme the importance of close liaison between the Sapper and the civil engineer, and it appeared that everyone was using the latter term on the present occasion in its original sense. Mr Wynne-Edwards had already pointed out some of the difficulties; but Mr Lloyd's personal view was that that liaison, which was of fundamental importance, should be built up immediately, because as had already been stated, it would not be possible to rely, in the next war, upon the initial period of comparative inactivity during the autumn and winter of 1939–40.

The 1914–18 war had seen the beginning of a realization that the civil engineer and the military engineer were inextricably mixed. The 1939–45 war had proved that beyond doubt, and any future war would have to take account of it right from the beginning. So far as the individual civil engineer was concerned, part-time liaison should be comparatively easy, because most of the civil engineers would either have had war service, or would have undertaken their National Service probably with the Sappers or with some similar Corps and would therefore have some knowledge of the problems. But in peace the fundamental difficulty was that the engineer had to earn his living in civil life as an employee. It was difficult even for a chief engineer to facilitate liaison with the Sappers. It was certainly much more difficult for less senior engineers.

In the nineteen-thirties some of the younger engineers who expressed views that there might be a military application of the work they were doing were usually told to apply their minds to what they were paid to do. Therefore it would seem that effective liaison would remain in the realms of pious hope unless there was some officially recognized channel or machinery set up for the purpose. In that event, the engineer in civil life, encountering a development which he felt should be discussed with the Sappers, would have a means of initiating discussion.

The Author expressed the opinion that, in a future war, it would be easier to repair installations than to start afresh. Most civil engineers would probably agree with that, especially those who had had experience in the Royal Engineers, because the major part of the time, labour, and material was concerned with the services required for the installations—drainage, roads, water-supply, power-supply, and so on. It occurred to Mr Lloyd that there was one problem to which the civil engineer in con-

sultation with the Sapper might address his mind. That was the question of the hutted camp or base installation.

Atomic weapons would have far more widespread blast effect than the ordinary bomb, and in his view it was desirable to have quickly erected hut and workshop buildings; easily assembled from prefabricated parts which could be replaced quickly. What shape would these buildings take? In World War II there was a shortage of timber, and square concrete structures were used; but was it not perhaps necessary to alter the shape? Would a blister shape avoid blast effect, and should it be set partly below ground level? That, of course, would raise problems of drainage. These were matters which should be investigated because the base installation was very expensive, and he felt certain that one could not abandon all the underground services which would have been provided.

A borough engineer who had recently visited the New York port authority had been given the use of a helicopter. It was reported that in company with the Engineer to the authority he dropped down and inspected drainage work in progress from the machine. How long would it be before every C.R.E. had a helicopter for reconnaissance purposes?

Finally, Mr Lloyd said he hoped that General Tuck would use his influence to ensure that on mobilization for a future war a suitable site is chosen for the R.E.O.C.T.U. He recalled that in 1939 when training started at Shorncliffe, there had been no bridging gap and one had had to be dug in the cliff-side; there had been no suitable demolition ground and no field-works ground, except a share in one occupied by a number of other units. Eventually enemy activity had made it necessary to move. Mr Lloyd hoped that the next time a site was chosen it would be such that engineer training could be accomplished with less difficulty.

Mr H. R. Lupton warmly welcomed the *rapprochement* between the military and civil engineer, of which this provocative Paper was an outward and visible sign. It had not always been like that. He well remembered as a junior Territorial infantry officer fixing up a mirror signalling system between battalion headquarters and the front line. It was invisible to the enemy and would have saved a great deal of trouble in mending wires broken by shell fire if the discovery had not immediately been made that he had one more heliograph mirror than was the proper ration of the battalion; although it was not wanted for any other purpose the system had been dismantled and the extra mirror returned to stores!

The situation was now very different and the fighting cock of war was effectively mated with the productive barn-door hen of civilian industry. "Productive" was the operative word—it was not the brain and the initiative of the hen to which he was referring. But in fairness to the barn-door hen it should be remembered that before she had been domesticated she had had to forage about for herself and for her chicks and to protect them against her enemies; but now she was hopper-fed. Could a moral be drawn from that? Engineers a century ago were certainly not

hopper-fed. They relied upon their own efforts and initiative for the knowledge they gained. Now there was, and must be, community-run research, and the works undertaken were of such magnitude that facilities for carrying them out had to be provided by the community. That did tend, perhaps, slightly to lessen initiative and willingness to take risks, and that, said Mr Lupton, must be watched.

The Author had claimed that the Royal Engineers would pioneer any new idea. The fighting cock was prepared to deal with any hen without troubling himself to decide beforehand exactly what colour the chicks would be! What an advantage for civilian engineers, to have the spur of the collaboration of an organization having so progressive an outlook!

As an illustration, Mr Lupton remarked upon the rate of development of new ideas during a war as compared with their progress in peace time. That was surely attributable to the collaboration then enjoyed with people whose chicks could not be of a predetermined colour, but who had to have interests and training wide enough to cope with their pioneer policy.

Colonel T. I. Lloyd referred to the Army's minor excavations termed "Field Defences" or, more fully, "Field Atomic Defences." They presented of course no abstruse engineering problem, but there would be so many of them throughout a theatre of war, during both offensive and defensive phases, that their aggregate volume entitled them to some professional consideration.

The Engineer-in-Chief had emphasized the importance of excavating field defences quickly, but there remained the problem of preventing their collapse. The weather and enemy artillery fire had always been catered for, but now atomic bursts had to be faced as well. It seemed that within certain ranges of an atomic burst the very field works which protected a man from conventional weapons, and from the heat and nuclear radiation of an atomic burst, would be likely to cause his death by collapsing upon him under blast or earth shock. Accordingly stronger field works were needed. Approximately, all excavations, even those in firm soil, ought to be revetted or shored as if they were in running sand. Against the air burst it was expected that it would be necessary to set the limited aim of countering an instantaneous pressure of 1½ ton per square inch. Against the ground burst, trenches and shelters had virtually to be earthquake proof.

Unfortunately, there was still great dependence on the 1918 methods of trench revetment and shelter construction, which required excessive time, skill and weight of stores for present-day conditions. There was, therefore, very considerable scope for the profession to solve that elementary but very extensive military problem by means of new techniques, which should be characterized by speed, simplicity, and use of minimum weight of stores.

The Author had referred to the resemblance between military engineering and the temporary work, using expendable stores, which occurred in

the preliminary stages of a large civil engineering project, and Colonel Lloyd thought that that resemblance was nowhere stronger than in connexion with the branch of military engineering termed " field defences," but which should be thought of more as " field atomic defences."

Mr E. H. Lewis-Dale suggested to the Author one additional factor in his distinction between the civil engineer's peace-time task and the military engineer's war-time task. It was the factor of cost. The civil engineer in peace-time did not necessarily make the cheapest job but his works had to be economically possible ; the military engineer in war-time had an almost free hand in terms of money, although he had to consider the cost in manpower (particularly in skilled manpower), scarce materials, and valuable plant. For example, a possible method of constructing airfields in time of war might be apt. It was known that research had been carried out into the use of metallic acrylates for soil stabilization, but as yet it would appear to be quite impossible in peace-time on account of cost. Research and development in the chemical industry might change that situation. In war-time it could probably be said that if those materials were not required for other purposes they could be used to build airfields.

In connexion with airstrips for modern and future aircraft, the present forecast must anticipate a strong surface extending over long distances. He suggested that when high-speed fighter aircraft were being considered it was also necessary to consider the question of very smooth surfaces. Bulldozers and graders were very versatile machines, but the actual surface of the strip itself had to be very smooth or else high-speed aircraft would run into severe trouble.

Mr Lewis-Dale had amused himself a short time ago by making what he thought to be an ingenious schedule of the things he would look for in a prefabricated pavement for airfields. The result was a very long list, but it seemed that most of the items should be considered by any one designing prefabricated pavement for use in war-time. The list was as follows :—

(1) A smooth surface.
(2) Suitability for use on difficult sites (clay, bad sand, etc.).
(3) Ease of transport of prefabricated units—compactness in terms of shipping space and lightness in terms of air transport.
(4) Ease of handling at site.
(5) Speed of assembly and laying.
(6) Economy in manpower.
(7) Strength.
(8) Minimum site preparation before laying.
(9) Minimum of ancillary stores. (For instance, prefabricated bituminous surfacing, known as P.B.S., required drums of bitumen, which were difficult and unpleasant to handle.)

(10) Cost and relative availability of material.
(11) Ease of maintenance when laid.
(12) Suitability for taking up and re-using.

Checking the characteristics of the various prefabricated tracks used during the 1939–45 war against the list, Mr Lewis-Dale had found that P.B.S. and Square Mesh Track could be labelled "fair"; Sommerfeld track was bad; bar-and-rod was indifferent; and Pierced Steel Plank (P.S.P.) was very good. Channel Track had not been used sufficiently in the war for it to be judged.

Mr H. J. B. Harding observed that the situation in a future war would appear to depend on whether atom bombs were dropped or whether the warring nations would refrain from their use in the same way that gas was not used in the 1939–45 war. If atom bombs were dropped then it would seem that most of the Paper became academic. It was difficult to think of troops building little shelters against atomic missiles. The civilian population was a much more profitable target for atom bombs, and that would raise a considerable problem of devastation, the overcoming of which would absorb a great deal of manpower.

What was most noticeable in a war was the greatness of the human spirit and the comparative smallness of the human mind, especially when wrapped in officialdom. When faced with a crisis ordinary human beings rose to the occasion and were demoralized when nothing happened. The apparent inactivity of the autumn and winter of 1939–40 might have been a respite for the Allies, but it did the enemy a great deal of good by simply leaving Britain alone and doing nothing, although Germany had the power. It was comparable with the position which obtained at the present time.

If the horrors of another war had to be faced, then some Members of the Institution would be Royal Engineers and others would have to work in the civilian field. There were organizations which had plant and executive labour at their disposal. There were other organizations which had highly technical men who planned. The organizations which executed the work were those which had sources of direct labour and were members of various bodies such as that represented by the Federation of Civil Engineering Contractors. The planning element was represented by the consulting engineers and Ministry departments.

In the 1939–45 war the Federation did a considerable amount of work in conjunction with the Director of Fortifications and Works, and various firms formed companies or sent men to the Royal Engineers. At the same time they were responsible for civic duties. In Mr Harding's own firm the members had been asked by various bodies whether they would look after this or that, and he personally had had five conflicting responsibilities, of which, fortunately, only two had materialized.

It was necessary to think ahead and consider the two possibilities—atom bomb or no atom bomb. Mr Harding had spent a long time during

the 1939–45 war in the East End of London repairing bomb damage, and during the first 2 years of ordinary raids he was repairing deep sewers, involving the excavation of tunnels, mains, and other services up to 30 or 40 feet deep. Every major incident took 5 months to repair, but they were all repaired in a permanent way. In those conditions permanent repair was wise, because they had not had to be disturbed since.

The effect of atom bombs was difficult to envisage. The picture would be frightening and very different. It was likely to be a question of abandoning areas rather than attempting to do anything about them at the time. That was an aspect on which there should be some information. If it were likely to happen, what was it necessary to provide? How was it going to be possible to get men to stay at war? It would be a great strain on the discipline of everyone.

In war it had always been necessary to try and keep the whole function of the city going by shopkeepers maintaining distribution, men being paid wages, and even in the worst times endeavouring to keep everything going on the same standards. Even now there was a Committee sitting trying to agree on terms of universal contract for the repair of war damage in the next war.

Lt-Col. J. B. Brown said he was speaking from two viewpoints—as a regular Royal Engineer officer and as a Member of the Institution.

The Author had stated in his introductory remarks that the regular officer of the Corps suffered from the fact that he tended to get snowed under with paperwork as he grew older and consequently became more and more an administrator and less and less an engineer. The Commandant of the School of Military Engineering had also described what was being done to teach the young Royal Engineer officer his job as a professional engineer. What was being done at present, with variations and with rather more intensity, was that which had been done by Lt-Col. Brown and people of his seniority when they were young officers.

When reading one of the journals of the British Section of the International Society of Soil Engineers, he had been struck by one Paper which referred to the work done by regular Royal Engineer officers in the field of soil mechanics in the middle of the nineteenth century. Some of the examples were very interesting, including one on retaining walls. It was interesting to note, apart from the technical aspect, that the Treasury allowed the officers to build experimental walls and knock them down again!

In that connexion, there was room for comparison between the Corps of Royal Engineers in the United Kingdom and the United States Corps of Engineers. The latter were much more fortunate in that they had a more expansive and less developed country in which to work, and had more opportunities of carrying out big engineering projects than the Royal Engineers; the American senior officers were fortunate in that respect.

Engineering in present times was becoming more and more specialized.

There were engineers who had specialized in roads and bridges, water-supply, and drainage, to name but a few. In civil life the civil engineer tended to specialize in one or possibly more of those subjects and had only a nodding acquaintance with some of the others. If Royal Engineer officers were allowed to specialize in one subject only, it would be found that in war the specialist in roads could only be sent to a place where there were roads to build, and he would not be of much use anywhere else. Therefore, it was probably dangerous to encourage engineer officers to specialize. A great deal of their job, he felt convinced, was in acquiring the actual experience needed to be able to judge the merits of the advice put over by the expert on his particular subject.

One of the points stressed in a book by Lewis and Maude [1] was that there were insufficient professional people with administrative experience or, to put it in another way, insufficient administrators with technical experience. Professional men tended to confine themselves to the professional aspect and to pay insufficient regard to the administrative aspect. He was not at all sure that was not part of the job of the engineer officer—to be able to administer a number of younger people who were experts in their own line. If the senior engineer officer was to do that, then he must be up-to-date and have a fairly reasonable acquaintance with all the more important lines of engineering which he was liable to have to handle in time of war. That was the problem—to give the more senior engineer officers, possibly from the rank of major upwards, more general experience.

How could that be done? Possibly senior officers in some theatres abroad, where there was a considerable amount of work in progress, might be able to visit more jobs being carried out by civil engineers. Another possibility was for the various Engineering Divisions of the Institution to invite some of the more senior engineer officers in their own areas to visit them when they were to hold their discussions.

Those were some of the lines along which it would be necessary to think if the two points of view from which he was speaking were to be co-ordinated.

Mr A. A. Osborne believed that all ideas, no matter how apparently fantastic, should be investigated. It had happened during the 1939–45 war that suggestions which had at first appeared ridiculous had turned out to be feasible and were sometimes excellent solutions of unprecedented problems.

The Institution had a vast membership, and in his view that membership could be used in exploring the fund of apparently fantastic ideas. In a Royal Engineers publication called the "Royal Engineers Training Memorandum," there had appeared in an issue some time ago a list of problems which it was desirable to solve, and officers were asked to submit their ideas. Mr Osborne suggested that the Institution could co-operate

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[1] R. Lewis and A. Maude, "Professional People," Phœnix House, London, 1952.

with the Corps of Royal Engineers on similar lines. He appreciated that there was, of course, a question of security, but if the Corps of Royal Engineers could list for circulation to all members, some of those problems to which there did not appear to be any immediate solutions, there might be some members who would come forward with usable ideas. If the Institution adopted Mr Osborne's suggestion, there might be a germ of an idea originated by a Member of the Institution, which with the Institution's closer co-operation with the Royal Engineers, who had all the resources of the Government at their disposal, could result in a difficult problem being solved.

Mr A. S. Quartermaine referred to the work that was carried out by the United States Army Corps of Engineers in peace-time on flood control, and similar work, and said that it was not done in Britain in peace-time except in an emergency. When the flood disaster occurred in January and February of 1953, not only the Royal Engineers but all the Services were very busy helping in the emergency. It would be of interest to learn whether the Author felt that there was a case for the use in the United Kingdom of Royal Engineers on civil work of a suitable character. By that he meant such work as the further improvement of sea defences, which would be desirable if it could be done without quite the same expense as would be incurred if all the work were done by civilian labour. The benefit would be that the Corps of Royal Engineers would get experience in that class of work.

*** **Mr A. C. Paterson** observed that the active defence forces maintained in peace to which the Author had referred would be called upon, together with such Reserve and Territorial Forces as would be mobilized with sufficient speed, to bear the brunt of the aggressor's attack and their lack of numbers could be compensated only by superior technique and superior equipment. In addition, however, there would have to be made available to the field engineers the maximum possible amount of controlled power. That power would take the form either of high explosives for demolitions or of civil engineering and other specially developed plant. Since too much plant would affect mobility, a balance would have to be struck and advantage taken of all possible power sources. There had been, in the 1939–45 war, a limited number of vehicles with power-driven winches and they had proved themselves invaluable. Mr Paterson suggested that all vehicles in a Field Army should be fitted as a matter of course not only with such a winch but also with a power take-off which could be used either directly to drive such plant as concrete-mixers, pumps, circular saws, etc., or to drive a compressor which would, in turn, provide power for pneumatic tools.

The Author had stated that the Services had far too many small power plants and had suggested that it might be possible to deliver electric power

*** This contribution was submitted in writing upon the closure of the oral discussion.—Sec. I.C.E.

by grid to forward areas. The difficulties of establishing and maintaining such a grid supply would indeed be formidable. To be of value it would have to offer a reliable supply with the minimum number of outages. To avoid risk of damage to the generators and transformers, a degree of electrical protection would be required little less stringent than in civil practice. The effect of a single shell or bomb might be widespread and the time required for repair considerable. The small power plants offered the advantages of dispersal and enabled units to operate anywhere irrespective of whether a grid supply was available. It might well be, however, that within the unit there were too many small power plants which could be replaced by one or two larger units, their size being limited by considerations of mobility. In such cases the development of the gas turbine might be of assistance. At the Engineering and Shipbuilding Exhibition at Olympia in 1953 the electricity-supply was provided by a gas-turbine set, simply placed upon a reinforced-concrete floor-slab, below which was a basement, and it had not been bolted down in any way. It had had a working rating of 750–900 kilowatts with a maximum output of 1,000 kilowatts and could take full load within 30 seconds of starting. These sets could be supplied to larger workshops and supply depots where the demand would justify their use and they could also be used for the small mobile power stations mentioned by the Author. The advantages of being able to dispense with the heavy foundations and elaborate cooling arrangements required for compression-ignition engines of comparable power were obvious, particularly under active service conditions. As had been announced in the Technical Press, such sets were now in series production and a number had been ordered by the Air Ministry.

The Author, in reply, referred first to the question of how much experience Royal Engineer officers received in their profession. To begin with, there was more construction going on than was perhaps realized outside the D.F.W.'s office. For instance, there was a new township being built in Germany for the new headquarters ; it was a complete town with all services and it was built on what had been virgin forest. That was one example of permanent construction in new work. The army moved about the world so much in the Cold War that there was a good deal of new construction going on overseas on roads and on semi-permanent buildings. The trouble was that it was difficult to obtain permission for permanent buildings when the treaty terms with the country concerned were not very permanent.

The second point was in connexion with how prospective war-time chief engineers were trained in peace. Thanks to the co-operation of Members of the Institution, an annual course had been started in which one senior officer, who had already reached the rank of lieutenant-colonel would spend a year with a firm of civil engineers to visit big projects all over the world, and to learn how a project was tackled right from the start in the office of the firm to execution on the site. If one officer a year were

trained like that, there would always be in the Corps eight or nine senior officers who should be capable by selection and by training of taking on the kind of £250-million job that Generals Hughes and Tickell had taken on in constructing the Egypt Base in 1940–42.

It was fervently to be hoped that an Engineer-in-Chief should never have to do what the Chief of the United States Corps of Engineers had to do, namely, to give evidence to Congress Committees and to wheedle money from the Government. The Author's impression was that although the American Army's waterways responsibilities were based on old traditions and gave invaluable engineering experience to their officers, they also involved the U.S. Engineers in seeking political support—Municipal, State, and Federal—for their projects. If the Royal Engineers became tangled up in politics, in spending public money, and in competition with private interests, the Army's constitutional integrity and status would be compromised. However, there was one job that he would dearly love to take on with the Corps, that was the development of the road system in Great Britain.

Reference had been made to the use of helicopters. They were remarkable vehicles and the Author had flown some distance in them. They were invaluable for engineer reconnaissance and much time was saved by their use. The technique of soil reconnaissance from the air by photography was being developed and for both inspection and photography the helicopter was ideal. It was also well suited to reconnaissance after an atomic explosion. So there were many advantages in the helicopter, except from the point of view of cost and maintenance. Helicopters were very expensive and it was possible to buy many light aircraft for the outlay on one helicopter. Unless they were made much more cheaply they would not become as universal as could be wished. The American Army had them in considerable numbers, but for every helicopter in the air there were about four on the ground being maintained. The Army would get some helicopters, but there did not appear to be much chance of having them in large numbers in the near future.

The suggestion concerning airfields was gratefully received, and he desired to mention again the point made by Colonel Brown, namely, that Royal Engineer officers could not afford, much as they would like to, to specialize too much. However, they did specialize a little. They specialized in survey, transportation, and construction, but if there were more specialization the Corps would lack flexibility. In war it was seldom possible to have the right man at the right place. The Royal Engineer must have a broad engineering education, and it was the Corps' tradition to be able to tackle any job anywhere.

Mr Wynne Edwards had suggested that one of the most valuable ways in which civil engineers could collaborate with the Royal Engineers in peace-time was by assisting them to keep up to date in the latest types of plant and in modern techniques. Although the civil engineer was not paid

to think about military matters, the possibility of a major war in which he would certainly be personally involved was not a matter to be ignored. The Author hoped that the initiative of the Institution, and the attention drawn by this Paper to various aspects of engineering in war-time, would encourage civil engineers to pass on their information and experience to the Royal Engineers. Mr Lloyd had recommended some officially recognized channel or machinery for liaison of that nature. The Author hoped that the recently formed Engineer Advisory Board would provide a solution to that problem.

The Author appreciated that the Sapper officer spent some years at the age of about 25 to 30 in field engineering and soldiering rather than in gaining engineering experience on large projects. Many officers were now involved in track making through forest in Mount Kenya and the Aberdares, and in Malaya. They were also making field defences, dirt roads, equipment bridges, and jeep tracks in Korea. He doubted if much more could be done in the way of long courses, simply because the Army had a "cold-war" job to do and could not spare more officers for courses of technical training. However, the existing arrangements for executive appointments in construction, transportation, resources, and survey as lieutenant-colonels and majors, taken in conjunction with civil attachments and with the young officers' academic training, should give the majority of Sapper officers an opportunity of reaching a fair standard of technical efficiency. The main difference between the Sapper and the civil engineer was that the latter specialized and that difference was unavoidable.

Finally, the Author was not altogether prepared to accept the notion put forward by Mr Harding that, because of atom bombs, the Paper became academic. Civil Defence in the United Kingdom was not discussed in the Paper, though the Royal Engineers in the United Kingdom would take their share with the civil engineers in dealing with such a disaster. There were two problems, first to defend the country against atomic attack and the second to survive the atom bombs which reached their target.

The solution to the first depended on military operations and on engineer tasks overseas. Indeed it could not be assumed that attacks on civil populations would necessarily take the place of sea, land, and air battles. The best way to win a war might still be to destroy the enemy's armed forces. Also, because of the range of modern weapons, the geographical limitation of invasion by an aggressor might be vital to the survival of Britain.

Nevertheless the problems of home defence mentioned by Mr Harding were of immense importance to engineers.

The Author wished to assure Mr Paterson that power take-off was specified for a wide range of vehicles and to thank him for mentioning

the military application of the gas turbine, which was being studied by one of the panels of the Engineer Advisory Board.

In conclusion, the Author wished to take the opportunity of thanking the members of the Engineer Advisory Board for the valuable service they were so generously giving to the Army.

The closing date for Correspondence on the foregoing Paper has now passed without the receipt of any communication.—SEC. I.C.E.

Paper No. 5954

"Plymouth 'B' Power Station"

by

Leslie Richardson, A.M.I.C.E.

(Ordered by the Council to be published in abstract form)†

General

Plymouth "B" power station will ultimately have a capacity of 189,000 kilowatts. The present installation consists of three 31,500 kilowatt turbo-alternators and three pulverized-coal-fired boilers, each having a steam raising capacity of 320,000 lb. per hour at 625 lb. per square inch gauge pressure, and 865° F. All the civil engineering works, however, have been completed for the whole project with the exception of one-half of the power house and a second chimney.

Site and Lay-out

The site adjoins the Plymouth "A" power station on the north bank of the Cattewater, the tidal estuary of the River Plym, which affords ample supplies of cooling water and permits the intake of seaborne coal. It is intersected by the Cattewater branch line and private railway sidings, and was occupied by industrial concerns and as a roadstone quarry. Because of this, only gradual possession of the site was obtained over a 12-month period, beginning in January 1949.

The sub-base was known to be limestone overlain by varying depths of quarry waste and filling. Site investigations were limited to inspection of the out-cropping rock and a geophysical survey, which indicated that the limestone lay fairly uniform and level east to west, and fell uniformly southwards from the toe of the quarry to some 10 feet below the sidings. This survey did not distinguish between bed-rock, and the fissured and weathered rock which overlay bed-rock on parts of the site.

The nature, and relatively small area of the 15-acre site, dictated the general lay-out. The coal intake and ash discharge are at the wharf, the coal and ash conveyors bridging the railway and sidings, and passing through the ash and dust bunker buildings. The coal conveyors continue to the coal store near the quarry face, and to the power house sited between the coal store and the sidings. The power house is encircled by service

† The full MS. and illustrations may be seen in the Institution Library.—SEC. I.C.E.

Fig. 1

Power House: West Elevation

Fig. 2

View of Wharf Construction at L.W.O.S.T.

roads, upon which are built the operations block, workshop, stores, garage, and canteen.

The switch houses are separated from the other buildings by the "A" station coal store, and are connected to the power house by cable tunnels.

Power House (Fig. 1)

All foundations are carried down to bed-rock. No engineering difficulties were encountered, but rock levels were very irregular, and the basement-floor slab over the area of the turbine house and boiler house is constructed as a suspended-floor slab supported on mass-concrete-sleeper walls.

The structural steel-framework is riveted and bolted, and carries the external brick cladding. Wind forces acting on the turbine house are transmitted through special struts at roof level to the bunker bay frame which forms the stiffening core of the structure. On the opposite side, wind forces acting on the precipitator and boiler houses are taken up in the double latticed portals of the precipitator house. Longitudinally, wind forces are taken up in the bunker bay by bracings in the end bays, by the bunker girders, and by stiffened connexions, and elsewhere, by vertical bracings transmitting the reactions from the wind girders to the ground.

Steelwork generally was erected with a 10-ton steam crane and a 5-ton electric crane, each travelling on bogies. These cranes were assisted in the placing of the roof girders by a 15-ton and a 20-ton guyed derrick with electric winches. The heaviest single lift was 27 tons, and the total weight of structural steel was 4,230 tons. The framework was erected in 18 months.

External walls are 13½-inch brickwork. All wall bearing beams, and turbine-house columns are encased in concrete, painted with one coat of bitumastic before brickwork was placed against it. Roofs generally are of precast-concrete units, and floors are either in-situ concrete or filler joist construction. All internal finish is of fair-faced brickwork, with the exception of the turbine house and annexe where there is a tiled dado with plaster above.

A feature in the construction of the turbo-alternator blocks was the method of supporting the templet foundation frame in the top of the block. Ledger angles were welded to the upstanding reinforcing bars, which provided a rigid seating for the frame, and enabled it to be set and maintained in position during concreting. A complete form of seven-ply timber panels was made for the blocks and erected in position, the external shutters were then dismantled and re-erected in lifts as concreting proceeded.

Switch House Excavations

In order to provide a site for the switch houses, quarrying operations were carried out which involved the removal of 43,900 cubic yards of

limestone from the face of a cliff about 60 feet high. An existing switch house and an open air transformer compound are situated at the toe of this cliff; the rock dipped steeply towards the compound, and care had to be taken to minimize vibration and fly rock. The face was benched in approximately 10-foot steps, the average charge was five 2-inch diameter holes 12 feet deep with 5 to 7 lb. of Victor "B" powder per hole. Blasting was carried out just before and just after normal working hours, drilling proceeding continuously. The average daily excavation was about 200 cubic yards, and the maximum 370 cubic yards.

The existing switch house was protected with wire netting, and the transformer compound with corrugated-iron roofing and a wall constructed of corrugated-iron sheetings set 2 feet apart and infilled with earth.

Wharf, Intake, and Outfall Works

L.W.O.S.T. is − 8·24 O.D. (Newlyn), and the rock level ranged from + 2·00 O.D. (Newlyn) at the downstream end of the site to − 96·00 O.D. (Newlyn) at the upstream end, almost all the difference in rock level taking place at a submarine cliff crossing the site about 370 feet upstream.

The wharf structure is 570 feet long, and has a reinforced concrete beam end slab deck supported on piers stiffened by precast-concrete bracings at low-water level. (See *Fig. 2.*) The front row piers are of 4-foot diameter spun-concrete tubes infilled with in-situ reinforced concrete, and they sit either directly on the rock or on precast piles. The cores of the 21-inch square hollow-piles are formed by 20 g. sheet-steel cylinders 4 feet long and 14 inches diameter, supported by cylindrical diaphragms which also act as pile forks. Reinforcement is by four 1½-inch diameter bars, welded at the joints. The concrete was vibrated, and the mix was 1 : 1 : 2. The piles, each initially 87 feet long, weighed 13 tons, and were driven to refusal with a 5-ton single acting steam-hammer with a drop of 4 feet.

To enable 2,500-ton colliers, with a loaded draught of 18 feet and a length of 300 feet, to approach the wharf and to provide a grounded berth for two vessels, dredging works were carried out. The dredge included 2,225 cubic yards of rock, and the time taken was 20 weeks, of which rock-breaking took 8 weeks, and grabbing 16 weeks.

Unsuccessful attempts at rock-breaking were made with a No. 9B3 McKiernan Terry hammer, slung from a crane already on the wharf, and with underwater drilling by diver and blasting. The work was actually carried out with a rock breaker capable of lifting and dropping through 20 feet a 15-ton weight 18-inches diameter and 20 feet long, fitted with a chisel point.

The cooling-water intake and outfall are incorporated in the wharf structure. The intake consists of a reinforced-concrete honeycomb box-structure, 116 feet long by 46 feet wide by 32 feet 3 inches deep, containing six screen chambers, two suction chambers, and two dry pump-pits, the

pumps working with a drowned suction. The floor level is 6 feet 9 inches below L.W.O.S.T. It was built on rock inside a sheet-piled cofferdam, which was satisfactorily sealed by placing a spoil bank in the river and sealing with concrete inside.

Inlet and outlet culverts are constructed as twin box culverts between the river intake, the power house, and the outfall. Under the power house they divide to form single box culverts, the inlet culverts lying between the outlet culverts. Each culvert can serve the whole station, each having a capacity of 156,000 gallons per minute at a velocity of 12·7 feet per second. The intake culverts are designed for a pressure head of 65 feet, and the outlet culverts for a head of 18 feet.

Purpose-made steel shutters were used for the internal faces of the culverts, and seven-ply timber panels for the external, the thickness of the concrete was 12 inches, and the mix 1 : 1·5 : 3. No special measures were taken at construction joints to ensure watertightness, other than to form V-shaped recesses in the first cast faces which were then cleaned, roughened, and plastered with 1 : 2 cement-sand mortar as concrete was placed against them. Vertical joints in walls were stepped in stages of 2 feet 6 inches, and the average distance between joints was 20 feet.

The outfall is 360 feet upstream of the intake, and is constructed of reinforced concrete. It consists of a funnel-shaped structure, the apron sloping down to the river bed from the penstock outlets of the culverts. It was constructed behind the existing masonry river wall at low tides when it was practicable for pumps to cope with the seepage through the wall.

Acknowledgements

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The Author is indebted to these firms for the assistance given to him in the preparation of this Paper, and to Mr A. C. Thirtle, Divisional Controller, South Western Division, British Electricity Authority, for his assistance and permission to publish.

The Paper is accompanied by twenty-four drawings and twenty-eight photographs from two of which the half-tone page plates have been prepared.

Paper No. 5956

"Concerning the Main Drainage of London"

by

Walter Protheroe Warlow, B.Sc. (Eng.), B.Sc., M.I.C.E.

(Ordered by the Council to be published in abstract form.)†

In 1856 the Metropolitan Board of Works was constituted and charged, inter alia, with the duty of maintaining the existing main sewers, and constructing works necessary to prevent the sewage from entering the river Thames within the area of the Metropolis. At the same time, vestries and local boards were formed and entrusted with the maintenance and construction of local sewers, the regulation of house drainage, and other responsibilities. The Metropolitan Board of Works was succeeded by the London County Council in 1889, and the duties of the vestries and local boards have been assumed by the Metropolitan Borough Councils.

The works constructed in connexion with the main drainage of London from 1856 to 1917 have been described in Papers presented to the Institution in 1865, 1897, and 1917. The present Paper includes a brief description of the most important works carried out between 1917 and 1951, of which the majority were completed by 1939; the Author reviews the development of the main drainage system, mainly in respect of the relief of flooding, from its inception and describes various features of the main drainage service.

Historical

The natural drainage of the area which became the Administrative County of London was afforded by a number of streams, most of which have been covered in, although a number south of the Thames remain as open watercourses.

The earliest legislation relating to sewers dates from the reign of Henry VI, and for centuries administration was entrusted to Commissions of Sewers. The early sewers were intended for surface water only, and until 1815, when water closets were coming into general use, the discharge of sewage into them was prohibited. The diversion of house drainage into the sewers, first permitted in that year, became compulsory in 1847. Whilst the drainage of houses was thus on the whole materially improved,

† The full MS. and illustrations may be seen in the Institution Library.—Sec. I.C.E.

the River Thames in the metropolitan area became seriously polluted and urgent demands arose for abatement of the nuisance. In the words of Sir Joseph Bazalgette :—

> "According to the system which it was sought to improve, the London main sewers fell into the valley of the Thames, and most of them, passing under the low grounds of the river before they reached it, discharged their contents into that river at or about the level, and at the time of low water only. As the tide rose, it closed the outlets and ponded back the sewage flowing from the high grounds; this accumulated in the low-lying portions of the sewers where it remained stagnant in many cases for eighteen out of every twenty-four hours. During that period the heavier ingredients were deposited and from day to day accumulated in the sewers; besides which, in times of heavy and long-continued rains, and more particularly when these occurred at the time of high water in the river, the closed sewers were unable to store the increased volume of sewage, which then rose through the house drains and flooded the basements of the houses."

Bazalgette, who had been appointed Chief Engineer of the Metropolitan Board of Works, submitted proposals for a solution of the problem, and after some delay these were approved and put into execution; although substantially complete by 1866, the works were not in operation in their entirety until about 1878. Briefly, Bazalgette's scheme involved the construction of intercepting sewers running from west to east, usually laid at a lower level than the existing main sewers, on each side of the Thames. Shallow dams in the inverts of the main sewers headed up the flow which fell through a connexion into the intercepting sewer below. When the flow in the main sewer was increased by rainfall to a greater quantity than the connexion was able to carry away, the surplus spilled over the weirs and continued down the course of the main sewer and so into the river. The intercepting sewers on each side of the river eventually converged on the outfall sewers which continued to outfalls at Beckton (Barking) north of the river, and Crossness on the south side. Here the sewage was stored during the flow of the tide and discharged during the ensuing ebb.

When these works were brought into operation, floodings were relieved to a very great extent, the condition of the waters of the Thames in the metropolitan area was considerably improved, and the unhealthy conditions from which many of the inhabitants living on low land near the river previously suffered owing to defective drainage were largely remedied. Meanwhile, however, the development of London proceeded rapidly, the population grew and later the waterproofing of roads increased the rate at which rainfall ran off into the sewers. Further, the usage of water per head of population, for which Bazalgette made apparently liberal provision, rose, leaving less space available for surface water in the intercepting sewers; consequently overflows into the river became more frequent, and

instances of flooding more numerous. Eight storm-relief sewers and four storm-water pumping stations were constructed by the Metropolitan Board of Works before its dissolution, and further extensive works, including extra intercepting and outfall sewers in addition to storm-relief sewers and pumping stations, were carried out by the London County Council. Nevertheless, floodings continued, and in 1919 Sir George Humphreys presented to the Council a comprehensive report on the main drainage system. By this time the area of land in the County of London available for building was restricted and fairly well defined. Thus it was possible, perhaps for the first time, to visualize the probable ultimate requirements of the County as a whole, and with experience of the vast network of sewers and pumping stations already in operation, to recommend with confidence a programme of works which would in ordinary circumstances virtually eliminate flooding of premises in the County during rainfalls of ordinary intensity, in so far as these were occasioned by high flood levels in the Council's sewers. The works recommended by Sir George Humphreys for early execution were commenced during his term of office and continued by Sir Pierson Frank who succeeded him in 1930. With a few unimportant exceptions they were completed by 1939. A decade of experience has shown how the extensive and costly works carried out between the two World Wars have supplemented those previously existing to provide for London a highly efficient main drainage service. It is, however, financially impracticable to provide a system of main drainage which would at all times eliminate the risk of flooding during exceptional storms, particularly in the case of basements or semi-basements below the soffit levels of the sewers which serve them.

The Drainage Area

The boundaries of the Metropolis, as defined by the Metropolis Management Act, 1855, were those of constituent parishes and agree closely with those of the present County of London. Notwithstanding that the Act was primarily a Drainage Act, the boundaries did not, as a rule, follow valley lines or watersheds and subsequently powers were obtained to authorize the reception into the London main drainage system of drainage from a number of adjoining local government areas. As a rule, the rate of flow is restricted in proportion to the population served and includes very little provision for storm-water. In three instances where the admission of out-county flow during exceptional storms might cause flooding in London, arrangements are provided to exclude the flow entirely when the flood level in the London sewer receiving the discharge reaches a certain height.

The area served by the London main drainage system in 1951 was 114,277 acres, and the estimated population was 4,571,500, of whom 3,348,336 were resident in the County. Using such estimates of future

population as are available, the ultimate population will be 4,030,800, including 3,250,000 in the County of London.

Although limited areas in the County near the periphery are drained on the separate or partially separate system, almost the whole of the area is served by combined sewers. There are in all some 65 outlets for storm-water from the main drainage system into the Thames and its tributaries. Eleven of these receive the discharge of storm-water from pumping stations and the remainder discharge by gravity. The storm-water outlets come into operation infrequently and occasions on which they are taxed to their full capacity are rare. For example, during 1951 the north-western storm relief sewer was in operation for a total period of about 50 hours and the highest rate of discharge reached during the year was less than two-thirds of the designed capacity. During the same year the aggregate time when one or more of the six pumps at Falcon Brook storm-water pumping station were at work was 91 hours; of this total six sets were in action together for only 1 hour, and a single pump was found to be sufficient to hold the flow for a total period of 57 hours 10 minutes.

In view of the number of outlets involved and the wide and rapid variations which occur in the rate and composition of the discharge, the Author suggests that it would be impracticable to assess with any acceptable degree of accuracy the quantity of putrescible matter discharged in storm-water into the river; since the intercepting and outfall sewers are continuously in operation, and discharges of storm-water are comparatively rare, the pollution of the water in the river from this cause may be less than is sometimes assumed.

Pumping Stations and Outfalls

Bazalgette's original pumps were of the vertical plunger type and with one exception were driven by beam-engines. The pumps next installed were single-acting rams driven by vertical compound or triple expansion steam-engines. Pumps of centrifugal type were first used in 1880, when they were driven by steam-engines. In 1892 gas-engines were first used for pumping storm-water in London, and this practice continued until 1929, since when Diesel engines have been installed to drive all new storm-water pumps. No steam pumping plant is now in regular use. Electric power is normally used at main pumping stations for the dry-weather flow but at each station storm-water pumps can be used for this purpose if required. It is little more than 20 years since all pumping of dry-weather flow was done by steam. In the interval the old pumps, many of them driven by beam-engines, have been removed and replaced in the same building, the stations remaining continuously in operation during the change-over. The change from steam to electricity has proved extremely satisfactory, and it is unfortunate that financial considerations preclude in existing circumstances the extended use of electric power for storm-water pumping.

TABLE 1.—PARTICULARS OF PUMPING MACHINERY AT MAIN PUMPING STATIONS (DECEMBER 1951)

Station	Lift		No. of pumping sets installed	Date of installation	Motive power	
	Average dry-weather flow: ft	Storm (max.): ft			Type	H.P. (each)
Western	21½	32	2	1938	Electric motor, A.C. commutator, 400V. 3 phase, 50 cycles	130
	21½	32	1	1937	Diesel engine, trunk piston, 6 cylinders, 4-stroke, vertical,	175
	21½	32	4	1936	do.	600
Abbey Mills	43	30	8	1931	Electric motor, synchronous induction, 2,200V. 3 phase, 50 cycles	600
	42	30	7	1912	Gas engine, 4 cylinders, vertical	475
	41	51	3	pumps 1926 engines 1937	Diesel engine, 2-stroke, 4 cylinders, compression ignition, vertical	360
	41	51	1	pump 1926 engine 1937	Diesel engine, 2-stroke, 4 cylinders, compression ignition, vertical	40
North Woolwich	50	14	2	1949	Electric motor, squirrel cage induction, 380V. 3 phase, 50 cycles	130
	50	14	1	1951	Diesel engine, 4-stroke, 3 cylinders, vertical	90
	50	14	1	1951	Diesel engine, 4-stroke, 3 cylinders, vertical	80
Deptford	24	35	2	1931	Electric motor, synchronous induction, 400V. 3 phase, 50 cycles	190
	24	35	1	1931	do.	290
	30	36	1	1933	Diesel engine, 4-stroke, 4 cylinders, vertical	325
	30	36	2	1933	Diesel engine, 4-stroke, 6 cylinders, vertical	500
	30	38	2	1933	Diesel engine, 4-stroke, 8 cylinders, horizontal	1,000

(*Continued on pp. 361 to 363*)

TABLE 1.—PARTICULARS OF PUMPING MACHINERY AT MAIN PUMPING STATIONS (DECEMBER 1951)

Drive	Pumps: Type	Pumps: Speed: r.p.m.	Pumps: Dia. of delivery: inches	Pumps: Capacity per set: cubic feet per minute	Total capacity of station: cubic feet per minute
Direct coupled	Vertical, mixed flow, single inlet	600	22	1,250	
Through bevel gearing	do.	600	22	1,250	29,550
do.	do.	266	42	6,450	
Direct coupled	Vertical, centrifugal, single inlet	214	48	4,500	
do.	Horizontal, centrifugal, double inlet	180	38	3,660	68,853
do.	do.	330	30	2,340	
do.	do.	500	8	213	
Direct coupled	Horizontal, centrifugal, single inlet	585	16	800	
do.	do.	550	16	800	3,200
do.	do.	550	16	800	
Direct coupled	Vertical, centrifugal, single inlet	273	27	2,600	
do.	do.	214	33	3,900	44,750
Through bevel gearing	do.	210	33	3,250	
do.	do.	180	40	5,400	
do.	Vertical, mixed flow, single inlet	283	60	10,800	

(*Continued on pp. 362 and 363*)

TABLE 1 (*continued*)

Station	Lift: Average dry-weather flow: ft	Lift: Storm (max.): ft	No. of pumping sets installed	Date of installation	Motive power: Type	Motive power: H.P. (each)
Crossness (Southern Outfall Works)	30	30	4	1940	Diesel engine, 4-stroke, 6 cylinders, horizontal	590
	30	30	2	1950	Diesel engine, 4-stroke, 6 cylinders, supercharged	400
	30	30	4*		Electric motor, synchronous induction, 3,300V. 3-phase, 50 cycles	525

* Installation in progress in December 1951.

(*Continued on p. 363*)

Particulars of the existing machinery at the main pumping stations are given in Table 1 reproduced herewith. In the Appendices to the Paper are given details of the original pumps, existing storm-water pumps, and a historical account of all pumping stations constructed in connexion with the main drainage of London.

The outfalls selected by Bazalgette are on the River Thames, west of Barking Creek on the north side and at Crossness, about two miles downstream, on the south bank. Whilst the original main drainage scheme effected a marked improvement in the conditions prevailing in the metropolis, it is evident that the effect on the waters of the Thames was that of the transfer of a large quantity of sewage from a number of outlets in the metropolis to two points some miles lower down the river, where insanitary conditions similar to those formerly experienced in London were eventually produced. A Royal Commission, appointed in 1882, recommended that the sewage should be purified before it entered the river, and chemical precipitation with lime and protosulphate of iron followed by sedimentation was introduced at both outfalls, the sludge being disposed of by dumping in the Thames estuary. The first results were disappointing. The original intention was to operate the sedimentation tanks on the " fill and draw " principle, but the quantity of sludge produced was only about one-third of that expected, and crude sewage was at times discharged into the river during heavy rainfall. Weir walls were then built across the tanks and the method of operation altered to " continuous flow." Improvement in the effluent was immediate, and the average quantity of sludge shipped at the northern outfall increased from 7,300 to 23,000 tons per

TABLE 1 (*continued*)

Drive	Pumps: Type	Speed: r.p.m.	Dia. of delivery: inches	Capacity per set: cubic feet per minute	Total capacity of station: cubic feet per minute
Direct coupled	Horizontal mixed flow, double inlet	320	38	4,500	
do.	do.	475	36	4,500	48,600
do.	do.	375	38	5,400	

week. The use of chemical coagulants was later suspended, but all sewage and storm-water reaching the outfalls passes through the sedimentation tanks, and at the northern outfall about one-third of the tank effluent receives further purification by activated sludge. Screenings are composted with crushed household refuse and the product, amounting at the present time to about 6,000 tons a year, is used as a low-grade manure. Tractor-driven scrapers are now used for sweeping the sludge along the floor of the sedimentation tanks. A pilot sludge digestion plant at the northern outfall has demonstrated that the sludge responds well to digestion and produces nearly 100,000 cubic feet of gas a day which is used for power and heating. The production of sludge gas will be greatly increased when a digestion tank formed in part of the disused old reservoir comes into operation.

The need for improved sedimentation at the northern outfall has long been recognized, and as a preliminary step the construction of detritus pits was started nearly 15 years ago, but suspended on the outbreak of war. Work on these has since been resumed and nears completion. The construction of new rectangular sedimentation tanks with mechanical equipment for removal of sludge is well advanced, and the Council has authorized the construction of further works for improvement of the effluents and for sludge digestion at both outfalls at an estimated cost of over £10,000,000.

Design

Bazalgette's original intercepting and outfall sewers were designed to carry off rainfall at an average rate of $\frac{1}{4}$ inch in 24 hours on the north side of the Thames and rather more than $\frac{1}{10}$ inch on the south side, in addition to sewage at the maximum rate of flow. The present practice, which has

been in force for many years, is to provide sewers and pumping plant sufficient to deal with a run-off of ¼ inch per hour from the drainage area, excluding only such large open spaces as the Royal and London County Council Parks. This figure is halved for certain areas drained on the partially separate system, and abnormally hilly districts require special consideration.

The formula used for designing the original outfall sewers was $v = 94{\cdot}2\ rs$, which Santo Crimp found to underestimate the flow, and by experiment he established a new formula which has since been used.

$$v = 124\sqrt[3]{r2}\,\sqrt{s}$$

Most of the sewers of the main drainage in London have been constructed in tunnel and are lined with brickwork. Gault or stock bricks were used for the older sewers, but for modern sewers red bricks from the Midlands have been generally used, the inverts of main, intercepting, and outfall sewers being faced with Staffordshire blue bricks to a level above the maximum dry-weather flow. So far as practicable side-entrances and ventilating shafts (which can be used as draw shafts) are provided at intervals of 800 feet. Ladders are used for access. Where access shafts exceed 40 feet in depth, refuges, or landings are provided at intervals not exceeding 40 feet. Two rings of brickwork are used for lining sewers up to 5 feet in diameter, three rings for sewers over 5 feet but not exceeding 7 feet 6 inches in diameter, and four rings for sewers over 7 feet 6 inches in diameter. No sewer constructed for the main drainage of London exceeds 11 feet 6 inches in diameter. In shafts, 9 inch brickwork is used down to 10 foot depth, 13½ inch from 10 to 30 feet and 18 inch below 30 foot. Cast-iron linings are used in lengths in which it is foreseen that compressed air will be required, and in certain circumstances elsewhere.

Typical details of brick sewers in open cut and in tunnel are shown in *Figs 1*, of cast-iron main and storm-relief sewers in *Figs 2* and of a side entrance and ventilator on a brick sewer in *Fig. 3*.

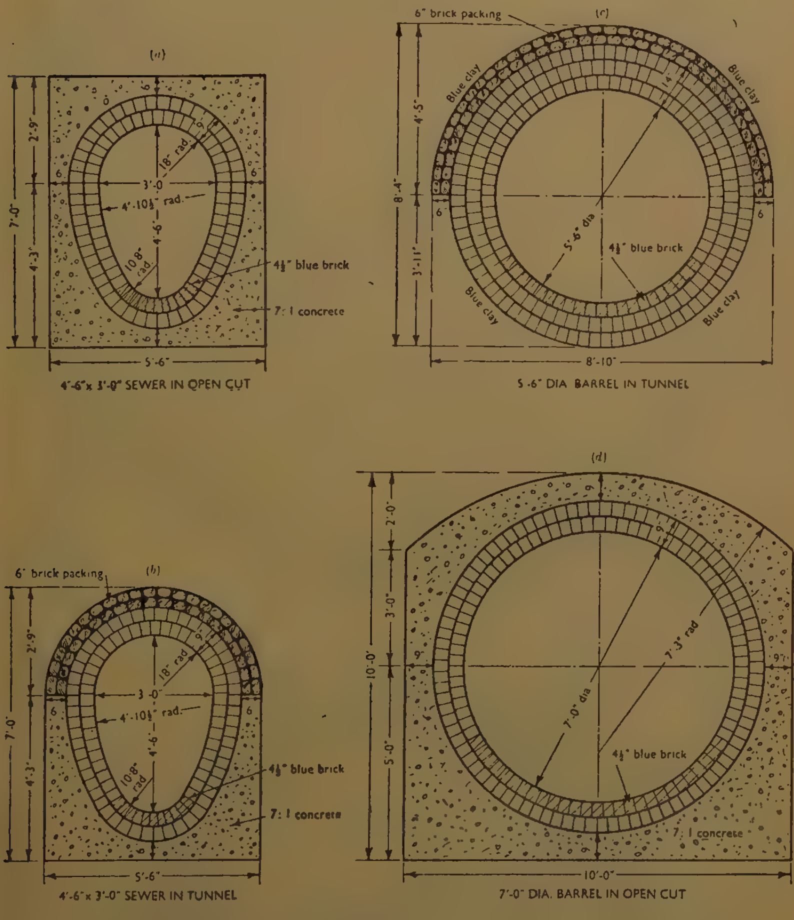
Organization and Administration

The Main Drainage Division of the Author's Department is responsible to the Chief Engineer for the management, operation, and maintenance of the main drainage and for the design of all civil engineering capital works in connexion with the service. The Divisional Engineer in charge of the division is assisted by an Assistant Divisional Engineer who supervises the central office staff, and two District Engineers respectively in charge of the two districts, west and east, in which the operational service is organized. The Marine Superintendent of the Council is responsible for the running of the sludge vessels under the general direction of the Divisional Engineer.

The professional and technical staff of the division is mainly employed on the design of capital works in connexion with the main drainage of

London, the design of sewerage in connexion with the Council's housing schemes (the capital cost of sewers constructed for the Council's housing estates from 1945 to 1951 was approximately £2,500,000), the disposal of sewage at the Council's establishments in rural districts where main drainage

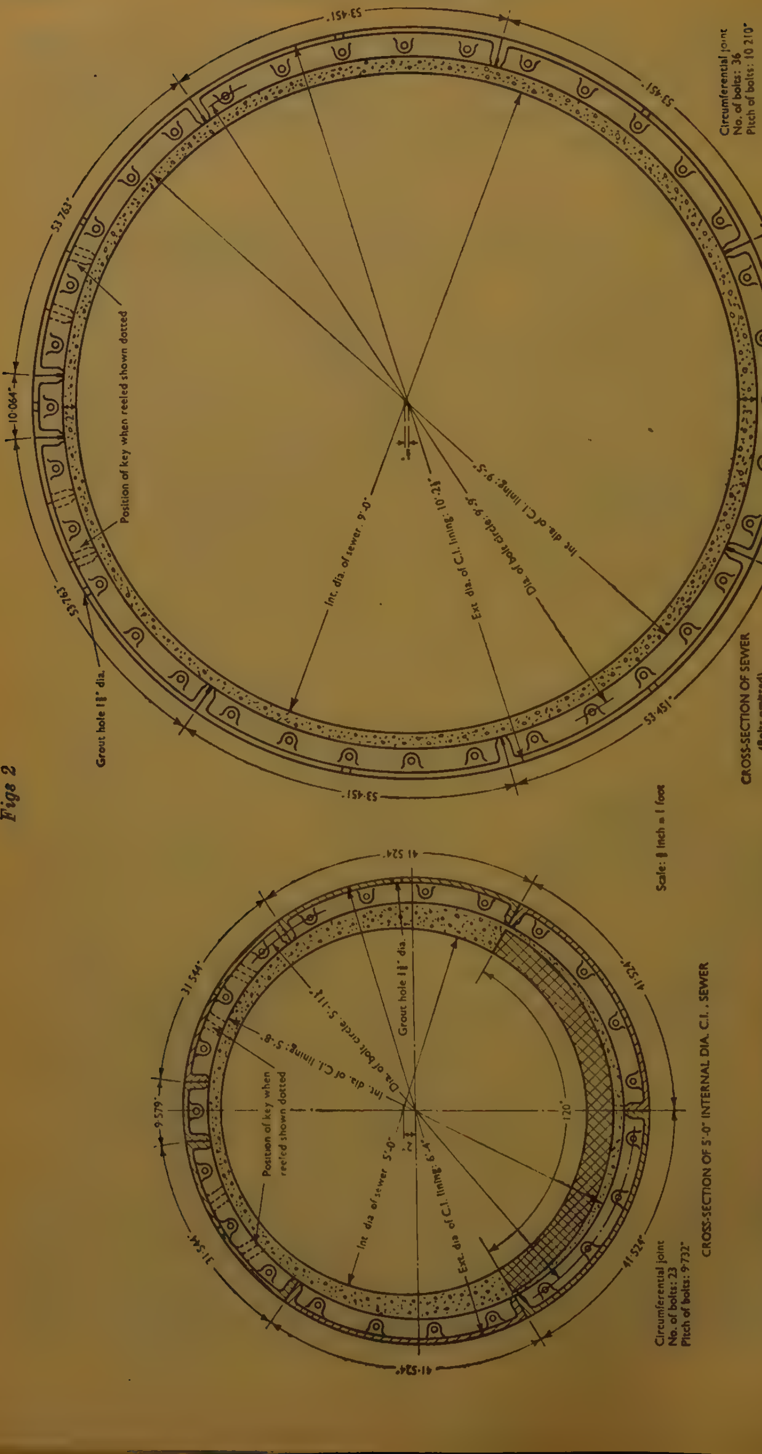
Figs 1



TYPICAL DETAILS OF BRICK SEWER IN OPEN CUT AND IN TUNNEL

facilities are not locally available, and a wide range of statutory and advisory duties. The Survey Section has been temporarily strengthened to carry out a complete re-levelling and partial survey of the sewers, occasioned mainly by the introduction of the Ordnance Datum (Newlyn), but affording incidentally an opportunity to correct discrepancies in the

Figs 2

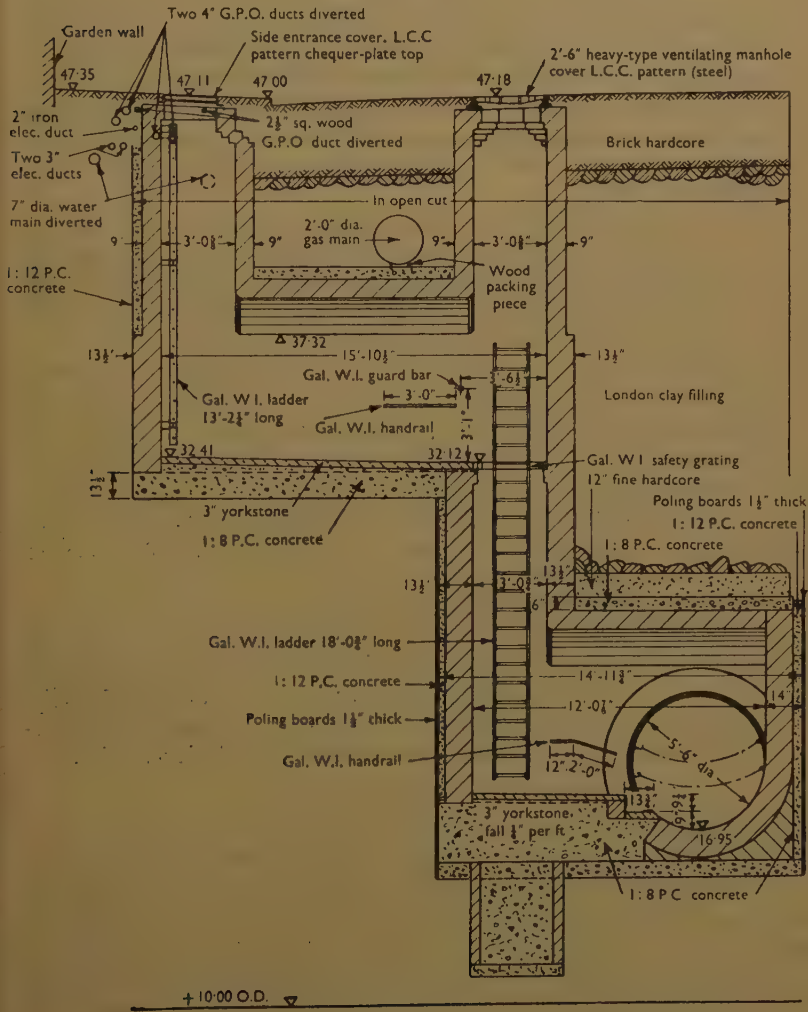


TYPICAL DETAILS OF CAST-IRON MAIN AND STORM RELIEF SEWERS

existing records occasioned by irregular subsidence of the subsoil of London, to which attention has been drawn elsewhere.

The western district includes all the sewers, one main, and five storm-

Fig. 3



Typical Side Entrance and Ventilator on a Brick Sewer

water pumping stations. Routine work in connexion with the sewers includes cleansing by direct labour, structural maintenance which is carried out by contract, and periodic campaigns for disinfestation. For control

and guidance in the provision of improvements for relief of flooding, records are available from 200 maximum-water-level indicators, 100 continuous water-level recorders and 22 recording rain-gauges. The portable huts formerly used by the flushing gangs have been replaced by self-propelled vans, equipped with facilities for heating water, and life-saving gear, in the use of which the men are trained. Each gang carries lead acetate papers, a "Spiralarm" detector lamp, and oxygen breathing apparatus. Men entering the sewers receive individual guidance on avoidance of bacterial infection. Some progress has been made in mechanizing the removal of sewer deposit, but the problem is complicated in London by frequent and irregular changes in cross-section which occur in some of the older sewers.

The importance of structural maintenance of sewers can hardly be over stressed, particularly in water-bearing ground where leakage into the sewer may erode the ground, undermine the subsoil, and cause subsidence at the surface. During the financial year 1951–52, £136,481 was spent on maintenance of sewers of the London main drainage system.

The eastern district is composed of four main and two storm-water pumping stations and the northern and southern outfall works. There is a chemical laboratory at each outfall, staffed by chemists, assistants, and samplers belonging to the chemical branch of the Public Health Department, and the efficiency of the service benefits greatly from the cordial co-operation maintained between the engineering and chemical staffs. Over 8,000 samples of sewage, effluent, and sludge and 4,400 samples of river water were examined in 1951.

There are at present three sludge vessels in service, each with a carrying capacity of about 1,500 tons. All are oil-burning twin-screw steamships, and during 1951–52 they made 1,151 trips, carrying 1,769,000 tons of sludge to sea. Normally, each ship makes a round trip of about 110 miles on every tide from Monday to Friday, with a four tide rest at the week-end. A fourth ship, of similar size to the existing vessels, is on order.

Trade Wastes and Ventilation of Sewers

The ventilation of sewers, which is generally effected in London by ventilators at street level, has exercised the attention of the Authorities since the days of Commissioners of Sewers, and the Paper includes a note on the attempts which have been, and are being, made to solve this problem.

London is expressly excluded from the provisions of the Public Health (Drainage of Trade Premises) Act, 1937, and the Council has little statutory control over trade effluents.

Finance

The total capital cost of the main drainage works from 1855 to the 31st March, 1952 was £19,187,913.

During 1951–52 expenditure on capital account was £384,017, and on Revenue Account £1,394,892, including £366,134 for debt charges.

Acknowledgements

The Author is indebted to Mr J. Rawlinson, C.B.E., M.Eng., M.I.C.E., for permission to include hitherto unpublished information regarding the main drainage of London ; to Mr W. A. M. Allan, M.I.C.E., his successor as Divisional Engineer (Main Drainage), for advice and criticism ; and to a number of his former colleagues in the Department, especially Mr F. C. Simmons, B.Sc., A.M.I.C.E., for invaluable assistance in the preparation of the Paper.

The Paper is accompanied by nine sheets of drawings, from some of which the figures in the text have been prepared, and by eight Appendices, from one of which Table 1 has been prepared.

Paper No. 5957

"Photoelastic Experiments on the Stress Distribution in a Diamond-Head Buttress Dam"

By

Professor A. W. Hendry, Ph.D., B.Sc., A.M.I.C.E.

(Ordered by the Council to be published with written discussion) †

SYNOPSIS

The Paper describes an experimental study of the stress distribution in a diamond-head buttress dam. The gravitational stresses were determined by the "frozen stress" photoelastic method, after the effective density of the model material had been raised by rotating the model in a large centrifuge. The hydrostatic stresses were found separately by the same method; the loading in this case was applied by a battery of small hydraulic rams. The gravitational and hydrostatic loads were combined to give the stresses in the dam when full. An analysis of the stresses in the model was carried out, using the method of calculation adopted for the actual dam and the results were compared with those obtained experimentally; reasonable agreement was obtained.

The stresses within the diamond head were examined by slicing the frozen stress models and by further tests on two-dimensional models. These were carried out to investigate, in particular, the effect of various holes passing through the head.

Introduction

The experimental investigation of the stress distribution in a diamond-head buttress dam, as described in this Paper, was carried out in connexion with the design of the Errochty Dam under construction in Stage II of the Tummel Garry Project of the North of Scotland Hydro-Electric Board.

The dam is made up of a series of buttress units roughly triangular in elevation having diamond-shaped heads, placed side by side with abutting faces sealed by thin metallic water-seals in such a way that each unit is free to act independently. The calculation of the stresses in a structure of this type is rather difficult and it does not readily lend itself to analysis by Airy stress-functions or even by relaxation. In addition, there are many factors difficult to assess, but which may have considerable effect on the stress-distribution in the dam. Examples are: non-homogeneity of concrete and its non-linear stress-strain characteristics, shrinkage and thermal stresses, and uncertain conditions at the foundations. Thus,

† Correspondence on this Paper should be received at the Institution by the 15th September, 1954, and will be published in Part I of the Proceedings. Contributions should be limited to about 1,200 words.—Sec. I.C.E.

great accuracy in the stress calculations is not to be expected and the design method of analysis is based on elementary statical principles. It was the object of this model-investigation to obtain a check on the validity of these calculations in the buttress web and to secure information concerning the stress-distribution in the diamond head. To achieve the first, an analysis of the model under the loading applied to it was carried out, using the same method as adopted in the design of the full-sized structure. The results of this analysis were compared with the experimental results; no attempt was made to "scale up" the model-stresses for comparison with the design stresses for the prototype on the argument that if the method of calculation gave the stresses in a small structure it would do so in a large structure of the same shape. Agreement would indicate that the method of calculation provided a reliable estimate of the primary stresses in an idealized structure; allowance for the complicating factors mentioned above would have to be made separately or covered by the factor of safety.

The stresses within the diamond head are not readily calculable by simple means and the experimental results were required to give a quantitative indication of the stress conditions which might be expected in the full-size structure.

The only feasible experimental method of obtaining these results was by the "frozen stress" method of photoelasticity. This has been known as a possible method for three-dimensional stress analysis for over twelve years,[1] and its validity has been established by Frocht,[2] Fisher,[3] and others. The procedure in carrying out a "frozen stress" analysis is based on the ability of certain plastics to retain, on cooling to room temperature, a photoelastic fringe-pattern developed by the application of loads at an elevated temperature. The model and loading gear are heated to a temperature of about 80° C., the loads are applied, and the whole apparatus is cooled slowly to room temperature. In the case of three-dimensional models, slices are cut at suitable inclinations and, upon examination in polarized light, are found to exhibit fringe-patterns from which the stress distribution can be deduced. At present the method is not fully developed and its application is limited by certain theoretical and practical difficulties. The former arise from the impossibility, in the present state of knowledge, of deducing the 3 principal stresses from the optical data except in special cases: the latter arise from imperfections in the materials available for making models.

In the present tests most of the stress systems examined were such that they could be regarded as approximating to two-dimensional systems. The freezing and slicing technique was however essential for studying the stress distribution in the buttress head and, in addition, the use of the freezing method made it possible to obtain measurable optical effects from the application of comparatively small loads; indeed, it was this

[1] The references are given on p. 396.

characteristic of the frozen stress method which alone permitted the experimental determination of the gravitational stresses.

Calculation of the Stresses in a Diamond-Head Buttress Dam

As has been mentioned, the stresses in the model under the equivalent hydrostatic and gravitational loading applied in the experiments were calculated by the same method as was used in the actual design work for comparison with the experimental results. It is not proposed to discuss the method of calculation, and only the general equations on which it is based will be quoted. A detailed consideration of standard methods of calculation is given in each of references 4 and 5.

In the calculations, the following assumptions were made with regard to the stress distribution across horizontal sections :—(1) There is linear variation of the vertical normal stress. (2) The stress through the thickness of the material at any distance x from the upstream face is uniform. (3) The neutral axis of the section is in the web of the buttress.

With the notation of *Figs 1* the total vertical force on a portion of the section to distance x is given by :

$$\frac{P}{A} \cdot a + \frac{M}{I} \cdot m$$

The vertical shear force on depth δh on the plane at distance x is :

$$s \,.\, b \,.\, \delta h = c \,.\, a \,.\, \delta h + w \,.\, h \,.\, B \,.\, n_1 \,.\, \delta h - \frac{\delta}{\delta h}\left(\frac{P}{A} \cdot a + \frac{M}{I} \cdot m\right) . \,\delta h$$

The shear stress on this plane as $\delta h \to o$ is :

$$s = \frac{c \,.\, a}{b} + w \,.\, h \,.\, B \,.\, n_1 - \frac{1}{b} \cdot \frac{d}{dh}\left(\frac{P}{A} \cdot a\right) - \frac{1}{b} \cdot \frac{d}{dh}\frac{M}{I} \cdot m$$

$$= \frac{c \,.\, a}{b} + \frac{w \,.\, h \,.\, B \,.\, n_1}{b} - \frac{P}{A \,.\, b} \cdot \frac{da}{dh} - \frac{a}{b} \cdot \frac{d}{dh}\left(\frac{P}{A}\right) - \frac{M}{Ib} \cdot \frac{dm}{dh} - \frac{m}{b}\frac{d}{dh}\left(\frac{M}{I}\right) \qquad (1)$$

All the differentials can be evaluated in terms of the known dimensions, forces, etc., and (1) is the fundamental equation for the calculation of the shearing stress across horizontal sections of the dam.

The horizontal force on any vertical plane of depth δh distance x from the upstream face is given by :

$$H \,.\, b \,.\, \delta h = wh_1 \,.\, B\delta h - \delta/\delta h \,.\, s\delta h = wh \,.\, B\delta h - \delta\int_0^x s \,.\, bdx$$

and the normal stress intensity as $\delta h \to o$ is :

$$H = \frac{1}{b}\left(whB - \frac{d}{dh}\int_0^x s \,.\, b \,.\, dx\right) \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \qquad (2)$$

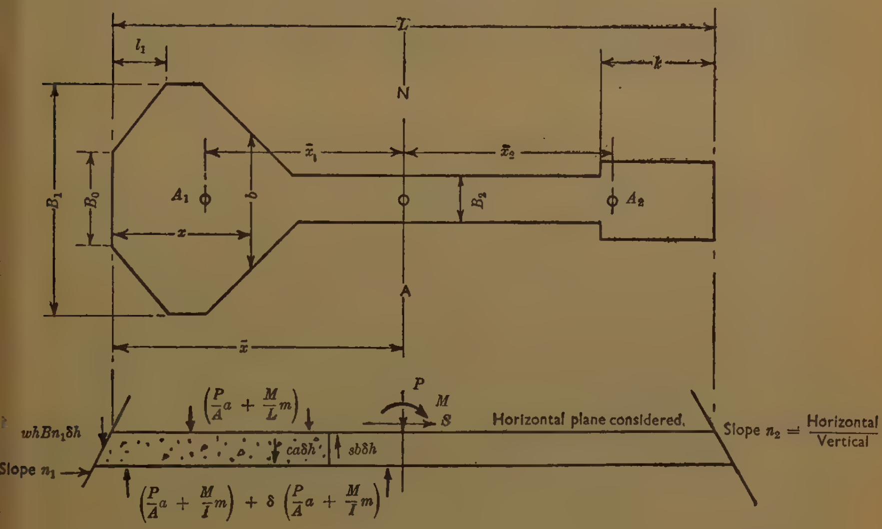
It can be shown that $\int_0^x sbdx$ can be written in the form :

$$\int_0^x s \,.\, b \,.\, dx = K_3 \cdot \frac{n}{b} + K_3(x - l_1) + K_1 a + K_2(a\bar{x} + m)$$

$$+ K_4(ax - a\bar{x} - m) + K_5[m(x - x) - I'] \quad . \quad . \quad . \quad . \quad (3)$$

where K_1 to K_5 are constants depending on the outline of the section.

Figs 1



h	denotes	head of water
w	"	wt of unit volume of water
C	"	wt of unit volume of concrete
p and q	denote	upstream and downstream vertical normal stresses
s	denotes	horizontal or vertical shear stress at any point distant x from upstream face
H	"	horizontal normal stress
A	"	total area of section $= A_1 + A_2$
A_1 and A_2	denote	portions of area upstream and downstream of neutral area
I	denotes	second moment of area of section about N.A.
I'	"	" " " portion from upstream face to distance x about N.A.
$\bar{x}$	"	distance of N.A. from upstream face
B	"	breadth of section on which water pressure acts $= B_1$ except where $x < l_1$
a	"	area of section to any distance x a_1 is area for $x = l_1$ a_2 is area for $x = L - K$
m	"	first moment of area about N.A. of section to any distance x –ve for areas upstream of N.A., that is, m is always negative, having a maximum numerical value at the N.A., and being zero for $x = 0$ and $x = L$
m_1	"	first moment of area of A_1 m_2 denotes first moment of area of a_2

Notation for Calculations

The separate terms of equation (3) can all be differentiated with respect to h giving an equation for :

$$\frac{d}{dh}\int_0^x s \, . \, b \, . \, dx.$$

The vertical normal stress across a horizontal section is calculated by the ordinary theory of bending. Having found the normal and shear stresses at points across several horizontal sections, the principal stresses can be found from standard formulae or by the Mohr's circle construction.

A stress analysis of the model was carried out on these lines for both the equivalent hydrostatic and the gravity loads for comparison with results obtained by experiment. The equations were rewritten in terms of a number of cross-sectional constants to reduce the labour of the calculations which, nevertheless, remained very lengthy.

Materials and Models

Two types of models were employed in the course of the investigation : (1) three-dimensional models of the whole buttress unit, and (2) two-dimensional models representing slices cut from the diamond head.

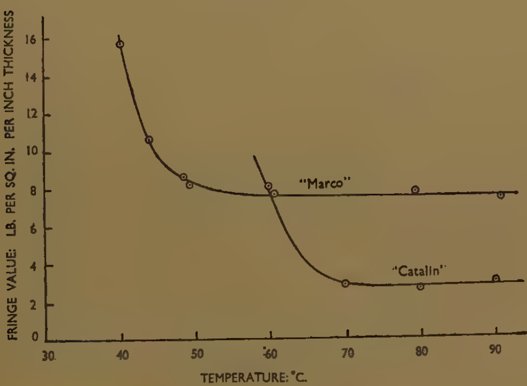
The three-dimensional models were made of the plastic " Catalin-800 " which was readily available in large blocks at a moderate price. The material was found to be relatively free from initial stress and its suitability for frozen stress work had been previously examined by Fisher.[6] Although not an ideal material, the above advantages, its favourable machining properties, and high stress-optical sensitivity led to its adoption. The main disadvantage of " Catalin " is that it develops a spurious stress system in the boundary layers arising from evaporation of volatile constituents when heated (known as the " rind effect ") ; this makes the accurate determination of boundary stresses very difficult. Alternative materials not suffering from this defect were either too costly or insufficiently developed at the time the work was undertaken.

In certain of the two-dimensional experiments the frozen stress method had to be employed and, as boundary stresses were required, the " rind effect " associated with " Catalin " precluded its use for these models. Consequently, " Marco " resin (now known as " Marcon ") a material of the polystyrene type, was employed since it is practically free from this defect. Compared with " Catalin," this material has a much lower stress-optical sensitivity and lower elastic moduli. The various constituents of " Marco " resin were supplied separately by the manufacturer ; the composition used in the present experiments was as follows :

64	Parts	by weight	" Marco " resin
28	,,	,,	" monomer " " C "
1	,,	,,	accelerator
1	,,	,,	catalyst.

Preliminary experiments were carried out on samples of " Catalin " and " Marco " resin to determine the correct temperature for the frozen stress experiments. The results are shown in *Fig. 2* in the form of a graph of unit fringe value (that is, the principal stress difference in lb. per square inch necessary to produce one fringe in a plate one-inch thick) on a base of temperature. " Catalin " is rather more than twice as sensitive as " Marco " in the photoelastic effect above the softening temperature which is about 70° C. for " Catalin " and 50° C. for " Marco " of the composition used. It appears that the exact temperature employed in a frozen stress experiment is not critical, provided that care is taken to ensure that the softening temperature is exceeded throughout the thickness of the specimen. In the experiments described in the Paper the " Catalin " models of the buttress were heated at 85° C. for a

Fig. 2

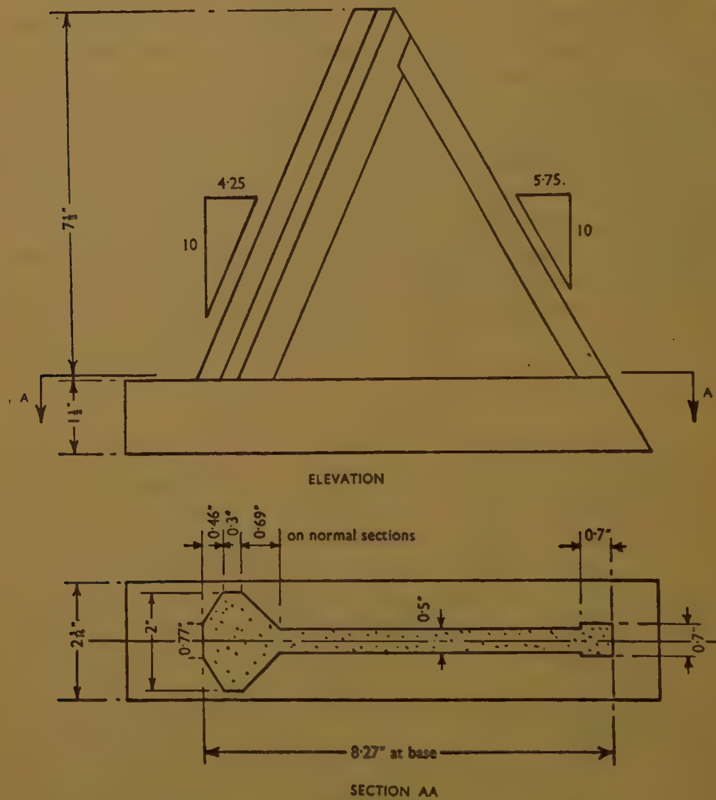


FRINGE-VALUE/TEMPERATURE CURVES FOR " CATALIN " AND " MARCO "

period of $1\frac{1}{2}$ hours before load was applied. The " Marco " models were heated to 72° C.

The buttress models were machined from triangular blocks of " Catalin " about $2\frac{1}{2}$-inches thick. They were first machined to $\frac{1}{16}$-inch oversize and were covered with a layer of vaseline to reduce the time-edge effect before final machining. This was carried out as quickly as possible, the model again being covered with vaseline when the final dimensions were reached. Machining stresses and other initial stresses were very small even in the considerable thicknesses of material involved. The dimensions of the buttress models are shown in *Figs 3*. The two-dimensional models were prepared from sheet material by hand cutting and filing.

Figs 3



THREE-DIMENSIONAL "CATALIN" MODELS

THE EXPERIMENTAL DETERMINATION OF THE GRAVITATIONAL STRESSES

The density of "Catalin" is insufficient to produce any appreciable stress from self-weight in a small model, so the effective density of the material was raised by rotating the model in a centrifuge at a speed which produced an acceleration field of approximately 40*g*.

Fig. 4 (facing p. 382) gives a general view of the centrifuge which consisted of a balanced rotating arm 10 feet 6 inches long driven by a 1½ h.p. electric motor through a gear box and V-belts. Speed control was effected by rheostats in the armature and field circuits of the motor. The radius to the centre of gravity of the model was 60 inches, and the speed of rotation to give a radial acceleration of 40*g* was 160 r.p.m.

The model, of the dimensions shown in *Figs 3* was heated, together with its immediate fixtures, in an electric oven at 87° C. for $1\frac{1}{2}$ hours. The model was withdrawn from the oven, an insulating hood padded with kapok having been drawn over it before the oven door was opened. It was then fastened to the centrifuge arm as quickly as possible. Once in position a double-walled aluminium cover was slid down over the model, the machine was run up to 160 r.p.m., and kept at that speed for two hours by which time the model had cooled down, freezing-in the centrifugal stress system.

To provide calibration of the fringe-pattern in the model, a 0·9 inch-diameter "Catalin" disk was placed inside a tube with its diameter parallel to the axis of the tube. A small steel piston rested on top of the disk in such a way as to subject it to a diametral load. This device was attached to the centrifuge arm close to the model so that it was subjected to the same centrifugal effect as the latter. A fringe-pattern was thus developed in the "Catalin" disk from the pressure of the steel piston. Examination of this pattern after an experiment enabled the fringe value for the model to be determined.

Preliminary experiments showed that the base conditions had considerable effect on the stress distribution in the model. This factor is not taken into account in the method of calculation which in effect applies to the top portion of a dam of infinite height. In practice, the dam is based on a semi-infinite bed of approximately the same elastic modulus as the dam itself. The stress system from the dam extends a considerable distance into the rock bed and, in order to reproduce this, the model should have rested on a large block of "Catalin," say, 12–16 inches deep. This, however, was impracticable and the effect of different base conditions was assessed by placing the model on a relatively unyielding layer of plaster of Paris and on a soft bed consisting of a $\frac{1}{2}$-inch-thick layer of "Beaverboard."

The "stress scale" for the gravitational experiments was adjusted to correspond to the arbitrary equivalent hydrostatic loading, described in the second part of this Paper, in such a way that:

$$\frac{\text{Weight of “equivalent water”}}{\text{Weight of centrifuged “Catalin”}} = \frac{\text{density of water}}{\text{density of concrete}}$$

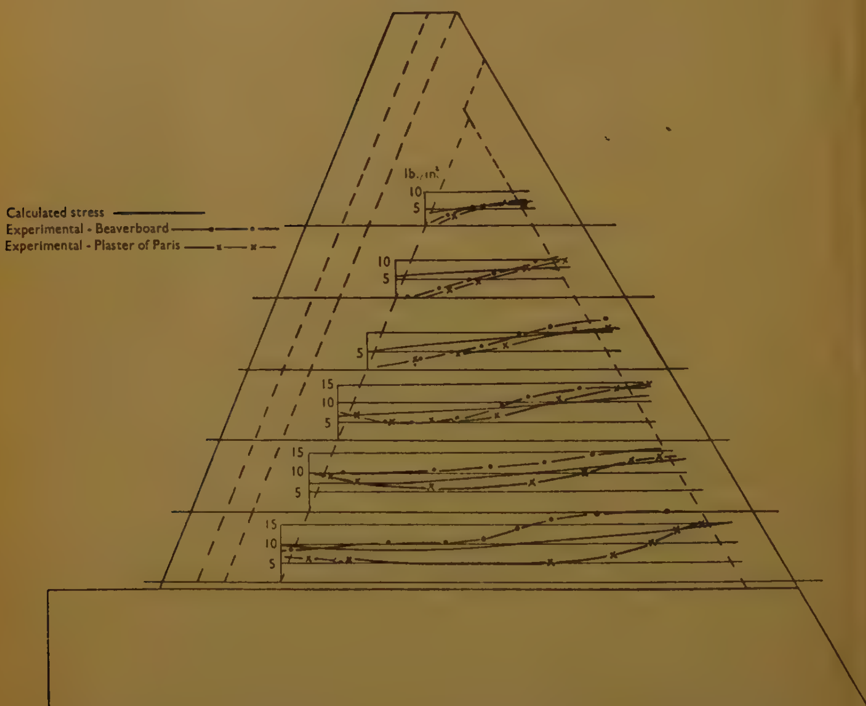
This was achieved by calculating the equivalent gravitational field for the hydrostatic loading and thence the acceleration field for the gravity stress model which would give the required ratio.

The centrifuge was run at an arbitrary speed, and the final adjustment was made by calculating the model fringe value from the calibration specimen, on the assumption that the acceleration field was in fact equal to that required for correspondence between the two models.

Fig. 5 shows the maximum shearing stresses across several horizontal sections as found by calculation and as obtained experimentally for the

two base conditions mentioned. This diagram reveals a fair measure of agreement between the calculated and experimental stresses. It will be observed that the values for the model resting on the plaster of Paris bed show somewhat better agreement than those from the model resting on the much less rigid "Beaverboard" base. In the latter case, the maximum shear stresses near the base are considerably higher than those

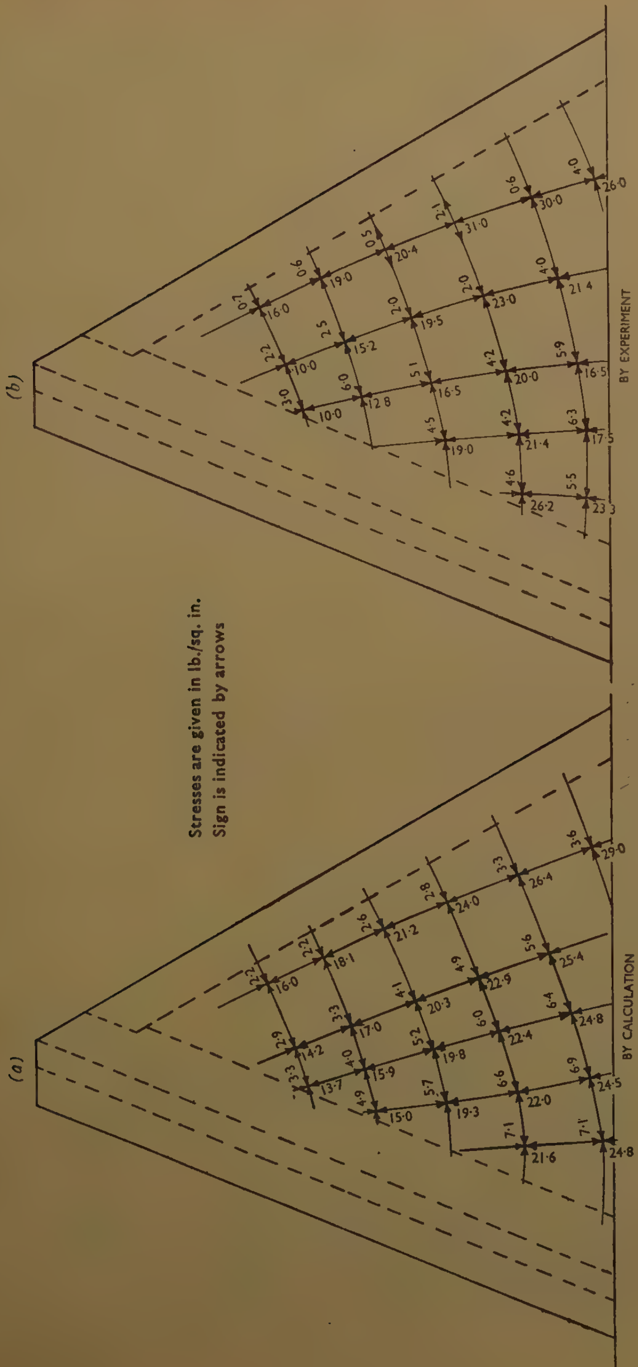
Fig. 5



MAXIMUM SHEARING STRESSES ON HORIZONTAL SECTIONS OF BUTTRESS WEB DUE TO GRAVITY

in the model on the plaster base, the calculated values being intermediate between the two. On sections near the top of the model the experimental results are almost identical: since the maximum shear stresses are almost horizontal, this suggests that the diamond head carries somewhat more horizontal shear than is assumed in the theory.

Further information concerning the stress distribution in the buttress web is embodied in *Figs 6* which show the magnitudes and directions of the calculated and experimental principal stresses for the model resting



Figs 6

PRINCIPAL STRESSES DUE TO GRAVITATIONAL LOADING

on the plaster of Paris bed. Although the separate principal stresses could only be calculated approximately from the experimental data by making certain assumptions concerning the boundary values, agreement is again reasonably good over most of the buttress. The main difference between the experimental and calculated compıessive principal stresses (Q) is near the base where the calculated values increase gradually from 25 lb. per square inch immediately behind the diamond head to about 31 lb. per square in h at the downstream boundary; the experimental stresses on the other hand are higher behind the head (27·5 lb. per square inch) and at the downstream boundary (38 lb. per square inch), decreasing to about 15 lb. per square inch at the middle of the base. The principal stresses, " P," are of the same order of magnitude both by experiment and by calculation. These stresses are very small; the maximum value attained was 7 lb. per square inch. The experimental results indicate a small tensile stress, 2 lb. per square inch, towards the downstream boundary of the web at about one-third height of the model; this, however, is very localized and would not be significant in a full-sized structure. These differences undoubtedly result from the conditions at the base of the model differing from those implied in the calculations.

Comparison of the direction of the principal stresses shows almost exact agreement between the calculated and experimental results. Slices were cut from the diamond head at various inclinations and revealed that the stresses in the head were too small for accurate measurement. These stresses are therefore small compared with those in the web. The most severe stresses in the head in fact occur in planes normal to the upstream surface under the action of the water-load. Consequently, a detailed analysis of the stresses in the head under gravity loading was not attempted.

As far as the buttress web is concerned it may be concluded that the calculations give a reasonable estimate of the magnitude of the gravitational stresses, although their actual distribution is somewhat more complicated than revealed by the theory owing to the base conditions.

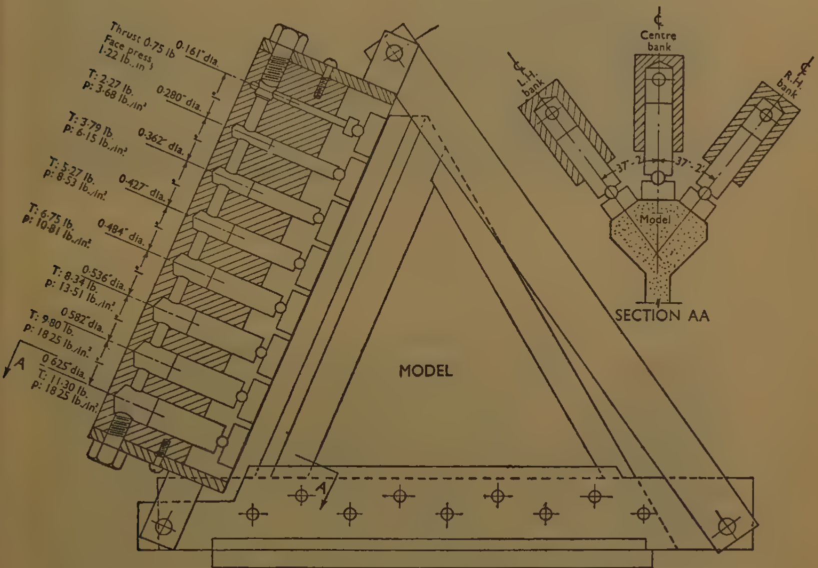
Experimental Determination of the Hydrostatic Stresses

The hydrostatic load was simulated by a battery of hydraulic rams (*Figs 7*) arranged in 3 banks to exert pressure on the 3 upstream faces of the buttress unit. There were 8 pistons in each bank, the diameters of which were varied to give a pressure-intensity increasing linearly from top to base.

All the ram cylinders were connected together and supplied with oil under pressure from a small hydraulic accumulator. There was no packing in the rams, oil leakage being avoided by the fit of the pistons. Each ram was calibrated at 85° C. by a frozen stress test on a " Catalin " disk, the material fringe-value being determined simultaneously from another

disk loaded by dead weight. After the first calibration test, it was found that a number of the pistons were developing considerably less than the expected thrust. This was remedied by reducing the diameter of the pistons by 0·0002 inches, re-calibrating, and repeating until the full thrust was registered.

Figs 7



Hydraulic Ram Unit

The model, of the dimensions shown in *Figs 3*, was fixed in the loading frame and heated in an electric oven at 85° C. for 1½ hours before applying the load. Thereafter it was cooled down slowly to room temperature over a period of about 4 hours.

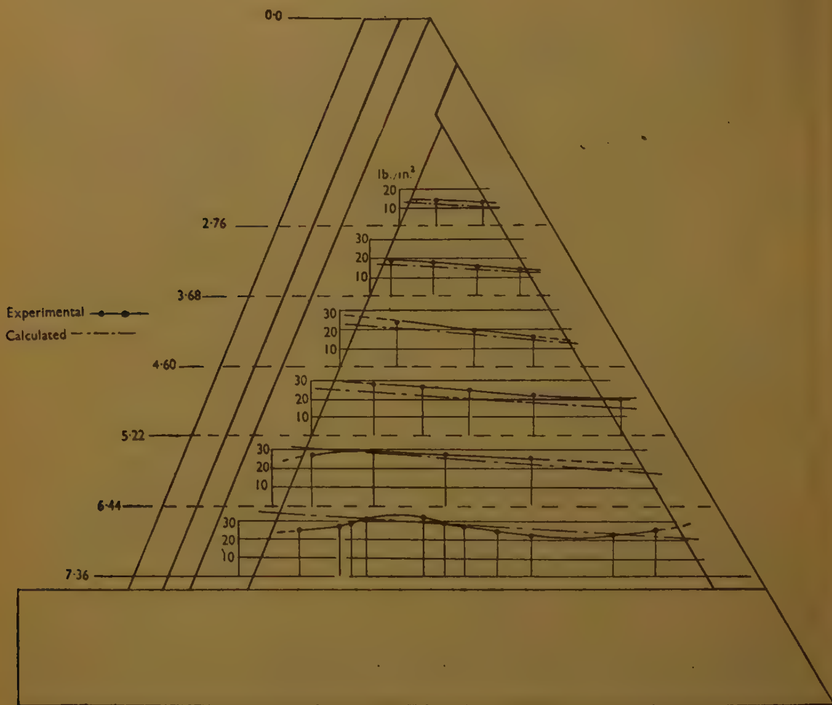
The face pressures applied in the test are given in *Figs 7*. Under these pressures the deformation of the model above the softening temperature was negligible.

The same results relating to the stress distribution in the buttress-web as given for the gravitational stress experiment are presented in *Figs 8* and *9*. In this case there is closer agreement between the calculated and experimental stress values. The "Q" principal stresses as calculated are somewhat lower than those obtained by experiment although the

maximum values, occurring near the intersection of the base and the diamond head, are practically equal.

The diamond head was cut into slices normal to the upstream surface and in the vertical plane of symmetry, as indicated in *Figs 10.* In the latter case, it was not possible to separate the principal stresses so that only values of P — Q were obtained. This gave only very partial infor-

Fig. 8



HYDROSTATIC LOAD ONLY. MAXIMUM SHEARING STRESSES ON HORIZONTAL SECTIONS OF BUTTRESS WEBS

mation concerning the state of stress on this plane, but comparison across 3 typical sections indicates that the calculated and experimental value of P — Q differ considerably. The results are shown in *Figs 11* from which it will be observed that the values agree towards the upstream face and at the junction of the head with the web. Elsewhere the calculated values fall far short of the experimental, which suggests that the shear stress in the head tends to concentrate towards the central axis instead

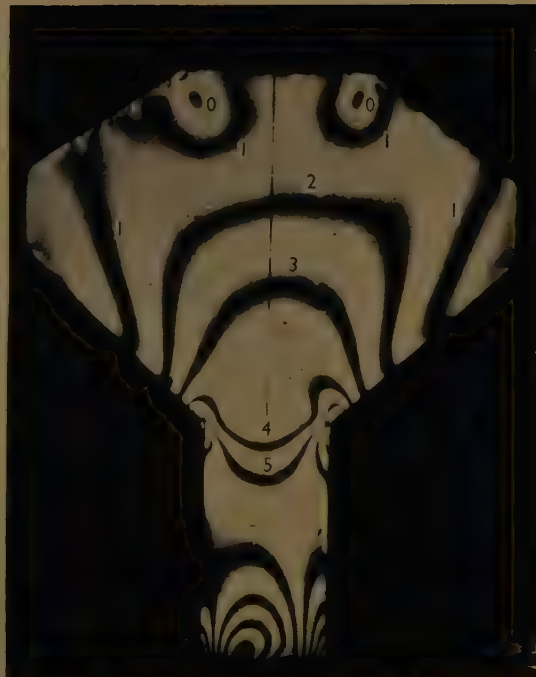
Fig. 4

Centrifuge for Gravitational Stress Experiments

Fig. 12

Fringe Photograph for Slice N.4 cut from Head of Three-Dimensional Model (1 Fringe $\equiv$ 14 lb./sq. in, P–Q)

Fig. 16

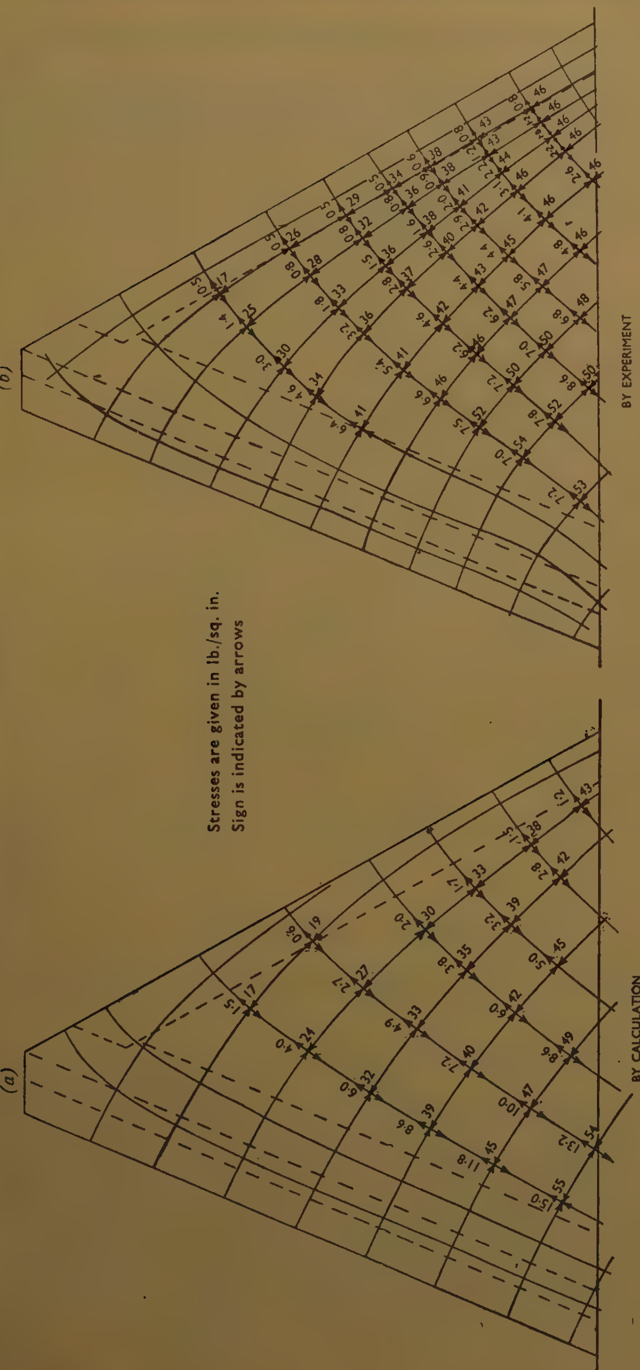


Fringe Photograph for Two-Dimensional Model of Diamond Head (1 Fringe $\equiv$ 74 lb./sq. in., P–Q)

Fig. 23

Fringe Photograph for Two-Dimensional Model of Buttress Head with Rectangular Gate Shaft; Section "D" in *Figs 21.* (1 Fringe $\equiv$ 65·3 lb./sq. in. for 100 lb./sq. in. Face Pressure)

Figs 9

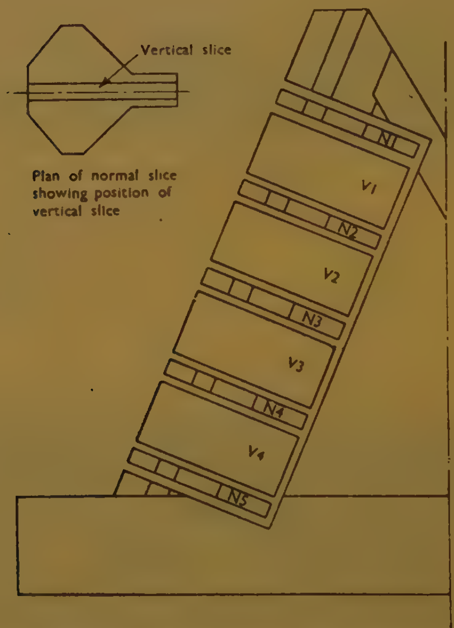


PRINCIPAL STRESSES DUE TO HYDROSTATIC LOADING

of being uniformly distributed on horizontal lines at right angles to this axis as is assumed in the theory.

The stress distribution in the diamond head on planes at right angles to the upstream face was investigated by cutting slices N1 to N5 (*Figs 10*). Since the third principal stress is approximately normal to these planes over the area of the head in slices N2, N3, and N4, the fringe-patterns shown by these slices were treated as two-dimensional stress systems and

Figs 10



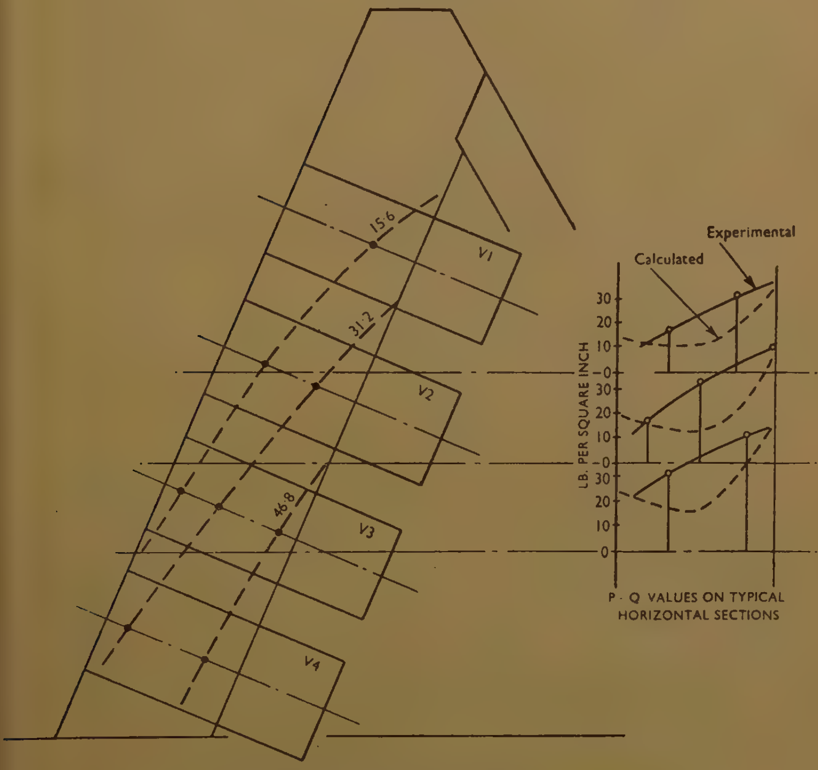
Elevation showing Positions of Slices cut from Three-Dimensional Model

analysed as such. Results are given here for slice N4 only, the others being qualitatively similar. *Figs 12*, *13*, and *14* show respectively the fringe-pattern, lines of principal stress, and principal-stress contours for the slice. The face pressure was 14·7 lb. per square inch. From this data may be obtained a general picture of the stress distribution in a typical normal section of the diamond head resulting from the hydrostatic pressure. As already observed, it was found in the gravity stress experiment that self-weight stresses in this plane are negligible in comparison with those from the water pressure. It will be seen that tensile stresses ranging from 20 to 30 per cent of the pressure on the upstream

face occur in the core of the head but no tension is developed on the boundaries.

In the actual dam, water pressure also acts over part of the face between adjoining buttress units as far as the water-seal, thus reducing

Figs 11

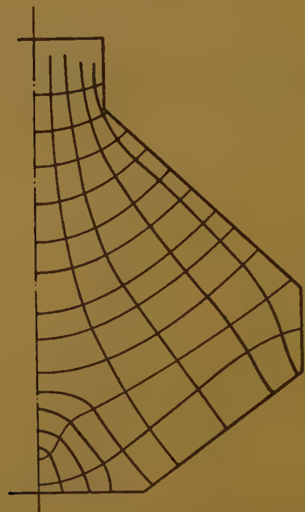


P–Q Values on Central Plane of Buttress

to some extent the tensions observed in the core. This effect was investigated by two-dimensional models, and is described later.

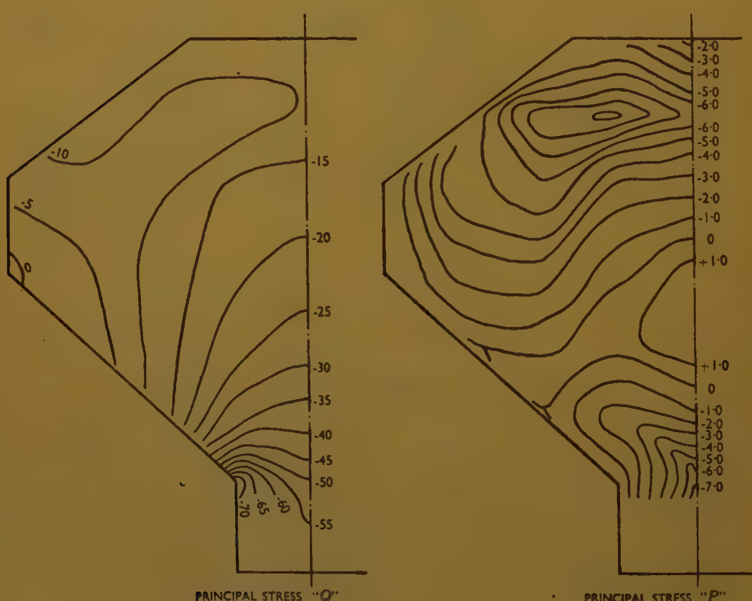
It was observed that the stresses in the lowermost slice (N5) were appreciably lower than those in the next one above (N4). This evidently arose from the proximity of section N5 to the base which would afford considerable support to the buttress head at this level.

Fig. 13

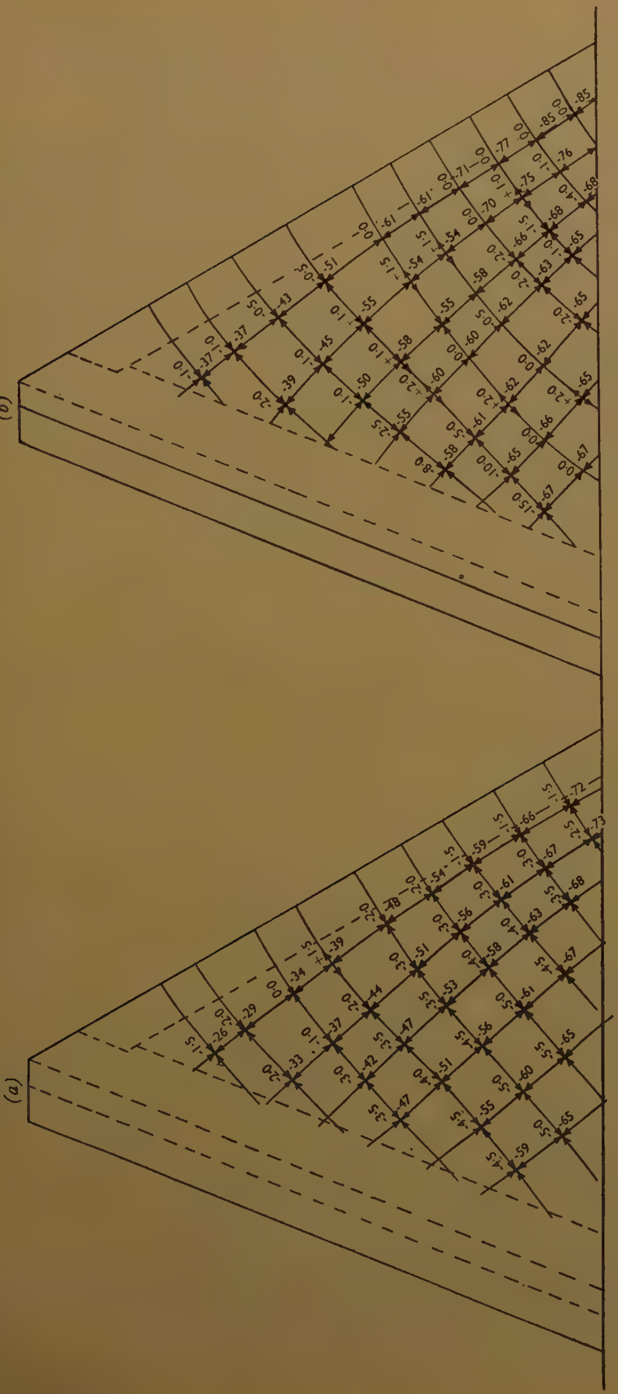


LINES OF PRINCIPAL STRESS IN SLICE N.2 CUT FROM THREE-DIMENSIONAL MODEL

Figs 14



PRINCIPAL STRESSES IN SLICE N.4
(+ denotes tension ; — denotes compression)



Figs 15

PRINCIPAL STRESSES. COMBINED LOADING

Stress Distribution in Buttress Web from Combined Gravity and Hydrostatic Loads

For the model resting on the plaster of Paris bed the stress distribution resulting from combination of gravity and hydrostatic loads has been worked out for both calculated and experimental results. *Figs 15* show the magnitude and direction of the principal stresses in the buttress web for this condition. Comparison of *Figs 15* (*a*) and (*b*) shows that there is reasonable agreement between the calculated and experimental stress distributions. In general, the experimental values of the larger principal stress tend to be higher than the calculated ones; the maximum value of this stress in both cases occurs near the base on the downstream boundary of the web. By calculation the maximum compressive stress is 75 lb. per square inch, and by experiment 85 lb. per square inch. The smaller principal stress does not exceed 7 lb. per square inch over the whole of the web both by calculation and experiment. Areas of tensile stress exist, but the maximum value is only about 3 lb. per square inch.

Having regard to the nature of the problem, the measure of agreement between the calculated and observed stresses may be regarded as satisfactory.

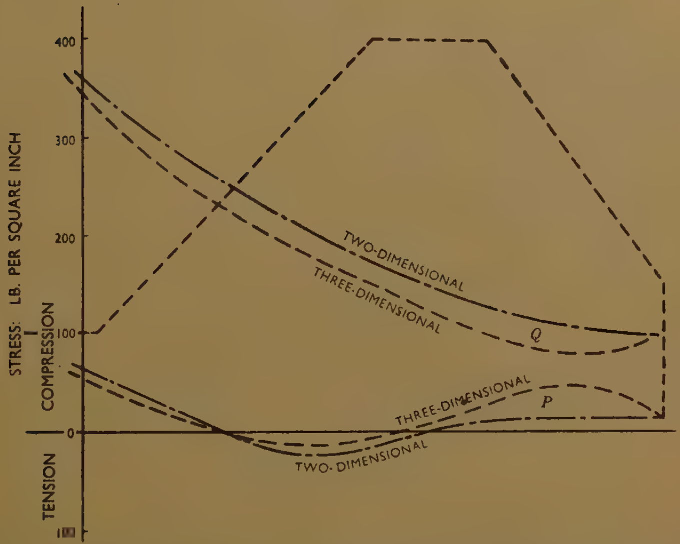
Experiments on Two-Dimensional Models of the Diamond-Head

A series of tests on two-dimensional models, representing sections taken at right angles to the upstream face, was carried out to obtain further information concerning the stresses in the diamond head and in particular to study the effect of various holes passing through the head.

A test was first carried out on a model of the same size and shape as the slices cut from the head of the three-dimensional model. This test was carried out by normal two-dimensional methods at room temperature, the loading having been applied to the three " upstream " faces by means of calibrated compression springs held in a suitable loading frame. The results of this test confirmed that the stress distribution in the two-dimensional model was qualitatively the same as in the slice from the three-dimensional model. An indication of the extent of the agreement between the slices and the two-dimensional model is given in *Figs 16* (facing p. 383) and *17* which show the fringe photograph for the two-dimensional model and the principal stresses along the central axis of a section of the head obtained for the two-dimensional model and slice N4. To afford a direct comparison in the latter diagram the stresses were adjusted to correspond to a face pressure of 100 lb. per square inch in both models. The fringe photograph may be compared with *Fig. 12*.

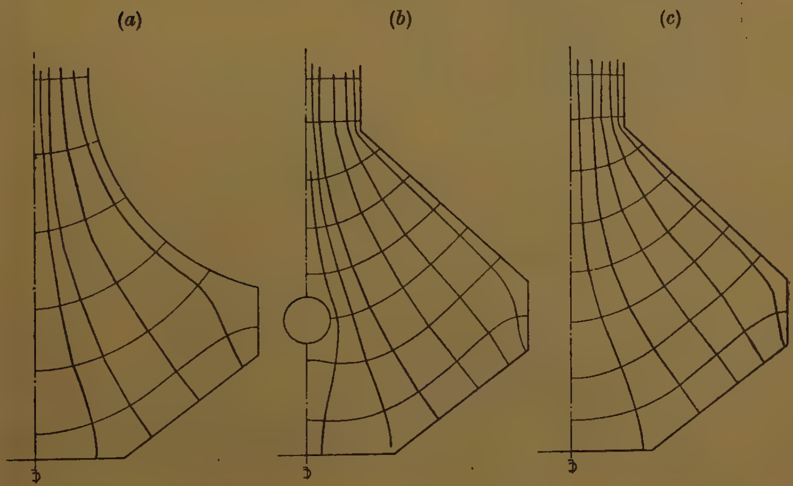
Having established that two-dimensional models would give a

Fig. 17



PRINCIPAL STRESSES ON CENTRAL AXIS OF NORMAL SLICE OF BUTTRESS HEAD

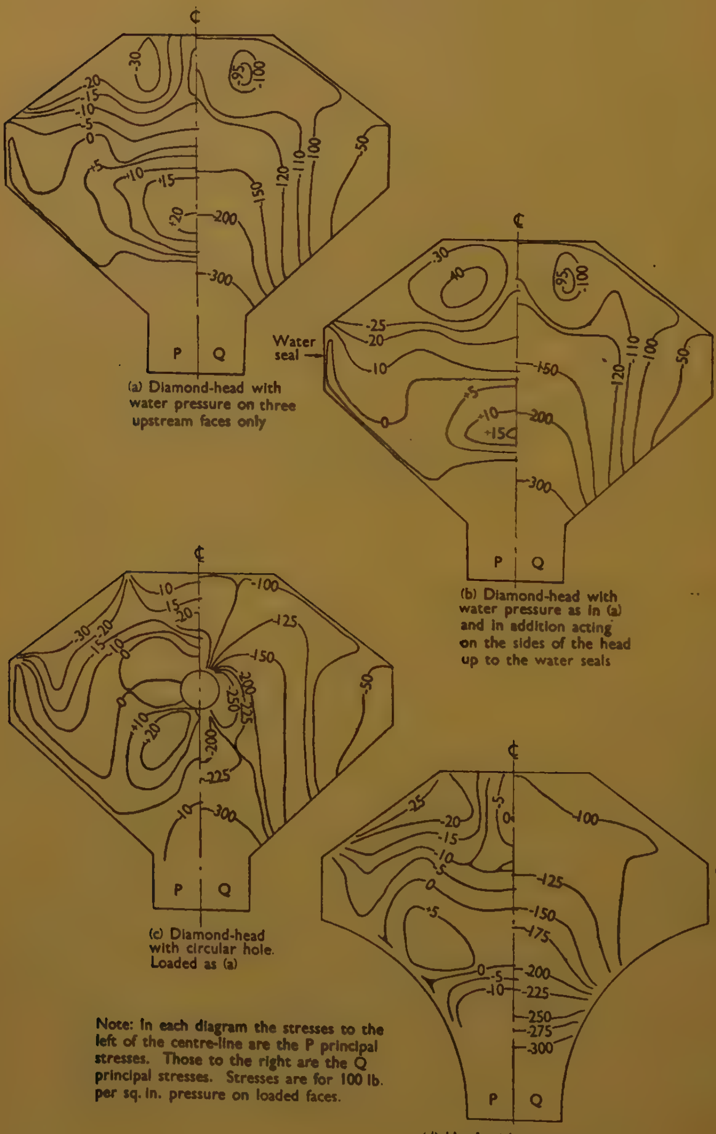
Figs 18



Original model | Model with central hole | Model with curved downstream hole

LINES OF PRINCIPAL STRESS IN TWO-DIMENSIONAL MODELS

Figs 19



(a) Diamond-head with water pressure on three upstream faces only

(b) Diamond-head with water pressure as in (a) and in addition acting on the sides of the head up to the water seals

(c) Diamond-head with circular hole. Loaded as (a)

(d) Head with curved faces downstream. Loaded as (a)

Note: In each diagram the stresses to the left of the centre-line are the P principal stresses. Those to the right are the Q principal stresses. Stresses are for 100 lb. per sq. in. pressure on loaded faces.

PRINCIPAL-STRESS CONTOURS IN TWO-DIMENSIONAL MODELS OF DIAMOND HEADS

reasonable indication of the stress distribution on normal planes in the diamond-head the following points were investigated :

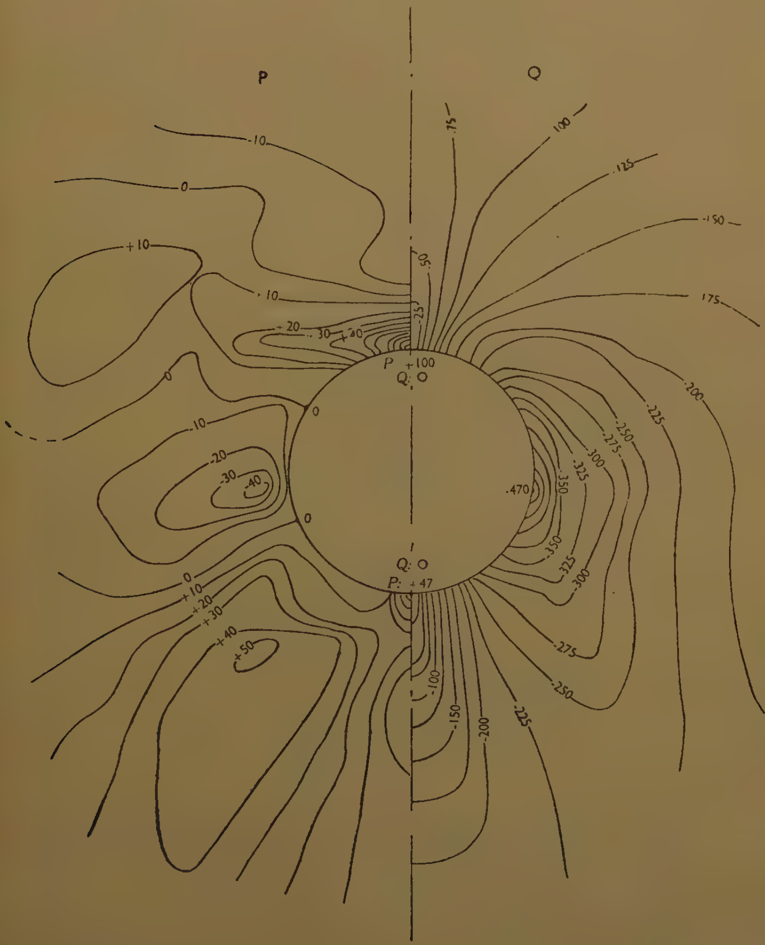
(1) The effect of water pressure acting on the side of the diamond-head up to the water-seal.

(2) The effect of a circular hole passing through the core of the head.

(3) The effect of altering the shape of the head.

(4) The effect of a large rectangular hole passing through the head at various distances from the upstream face.

Fig. 20



Principal Stresses around Circular Hole in Diamond Head

Space precludes detailed discussion of all the experiments so that only a few typical results are presented. *Figs 18* and *19* show respectively the lines of principal stress and contours of principal stress in models illustrative of (1), (2), and (3) above. Model " A " was loaded on the 3 upstream faces only, as in the case of the three-dimensional model. To determine the effect of water pressure acting on the side of the head up to the water-seal, a model was tested with pressure applied to this part of the head only, and the resulting stresses were superimposed on those obtained for Model " A " to give the stress system of Model " B " in *Figs 17* and *18.* The effect of the side water pressure was to reduce the tension at the core of the head from 20 lb. per square inch to 15 lb. per square inch with a corresponding increase in the compressive stresses parallel to the upstream face at points nearer the latter. The larger principal stresses were practically unaffected. In this, as in all other experiments of this series, the results are for a face pressure of 100 lb. per square inch.

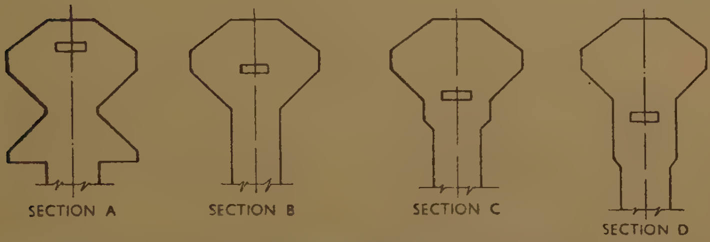
The effect of a circular hole passing down the centre of the head was next examined (see *Figs 18* (*b*), *19* (*c*), and *20*). Examination of these results and comparison with corresponding results for the previous model shows that the stresses in the head are not greatly increased by the presence of the hole, except in the immediate vicinity of the latter where the maximum compressive stress rises to 474 lb. per square inch and the maximum tensile stress to 100 lb. per square inch. Both these values occur only at points on the periphery of the hole. There are, in addition, zones of tensile stress on each side of the centre line downstream of the hole with maximum values of almost 30 lb. per square inch. A further experiment indicated that the maximum tensile stress at the hole would be reduced to 67 lb. per square inch by the action of the side water pressure.

Several alternative shapes for the head of the dam were examined by means of two-dimensional models, but only one of these modified shapes appeared to offer any appreciable improvement in the stress distribution as compared with the original design, namely, a head in which the downstream faces are curved instead of straight. An analysis of a head of this shape is shown in *Figs 18* (*c*) and *19* (*d*). From these it will be seen that the tensions in the core are substantially reduced, but whether the additional complication of constructing a head of this shape would be worth while is rather doubtful.

The final experiments on two-dimensional models were concerned with the stresses in the head of a special buttress which has to accommodate the ground sluice of the dam. In this buttress, a gate-shaft passes vertically through the diamond head starting close to the upstream face at the top and meeting the ground-sluice passage in the web, the thickness of which is increased in this buttress. The lower end of the gate-shaft is open to the water in the reservoir and consequently the walls of the shaft are subject to hydrostatic pressure. In order to investigate the

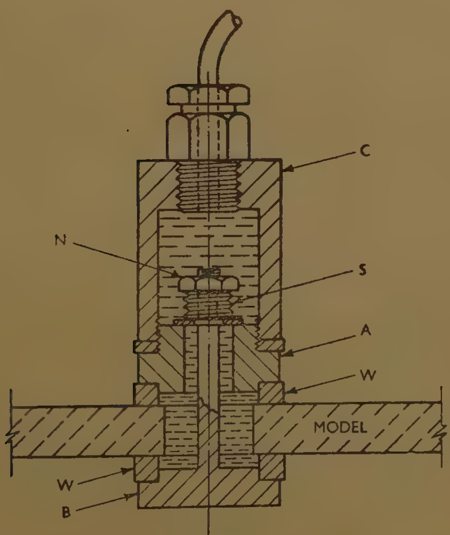
stress distribution in the head of this buttress 4 two-dimensional models were tested, representing sections at different levels. The diamond head was of the same general dimensions as in the previous tests but the web

Figs 21



Normal Sections of Special Buttress, Showing Position of Gate Shaft at Various Levels

Fig. 22



Device for Applying Pressure to Hole in Model

was thicker and the first section near the top of the dam was fish-tailed downstream because this buttress also carries part of the spillway. The shape of the models will be seen from *Figs 21.*

The fact that pressure had to be applied to the walls of the hole as well as to the upstream face introduced certain practical difficulties which were overcome by the employment of the freezing method and the use of "Marco" for the models. The high photoelastic sensitivity of materials in a frozen stress experiment meant that a satisfactory fringe-pattern resulted from the use of very low pressures compared with those necessary for a test at room temperature; the use of "Marco" ensured that the fringe-pattern was not distorted near the edges of the model as happened in the slices cut from the three-dimensional models. Pressure was applied to the upstream faces of the model by 3 of the pistons of the ram unit used for the complete buttress tests and to the hole by means of the device shown in *Fig. 22.* This unit was held in position by the spring S gripping together the two parts A and B. The compression of the spring was so adjusted by the nut N that leakage was just prevented when oil pressure was applied. Greased rubber washers, W, were inserted to enable the gripping pressure to be reduced to a minimum and so avoid interference with the deformation of the model. Oil under pressure was supplied, from a small hydraulic accumulator, at the top of the bell-shaped cover C.

The fringe photograph obtained for one of the models (*Section* "*D*," *Figs 21*) is shown in *Fig. 23* (facing p. 383), whilst the lines of principal stress and principal stress contours are presented in *Figs 24.* Examination of these results indicates the presence of rather high local tensile stresses at the corners of the holes and suggests that to avoid cracking these corners should be rounded. Tensile stresses also exist along the walls of the holes, and, below a certain depth in the actual dam, some reinforcement would be necessary around the gate-shaft.

In all the two-dimensional models, stresses are given for a pressure of 100 lb. per square inch acting on the upstream side. To estimate the stress conditions in the full-sized structure the model stresses should be multiplied by the ratio :

$$\frac{\text{Face pressure at the corresponding level in the dam}}{\text{100 lb. per sq. in.}}$$

Thus, at Section "D" of the special buttress the face pressure on the dam will be 55 lb. per square inch and the stresses in the head will be 0·55 of those in the model.

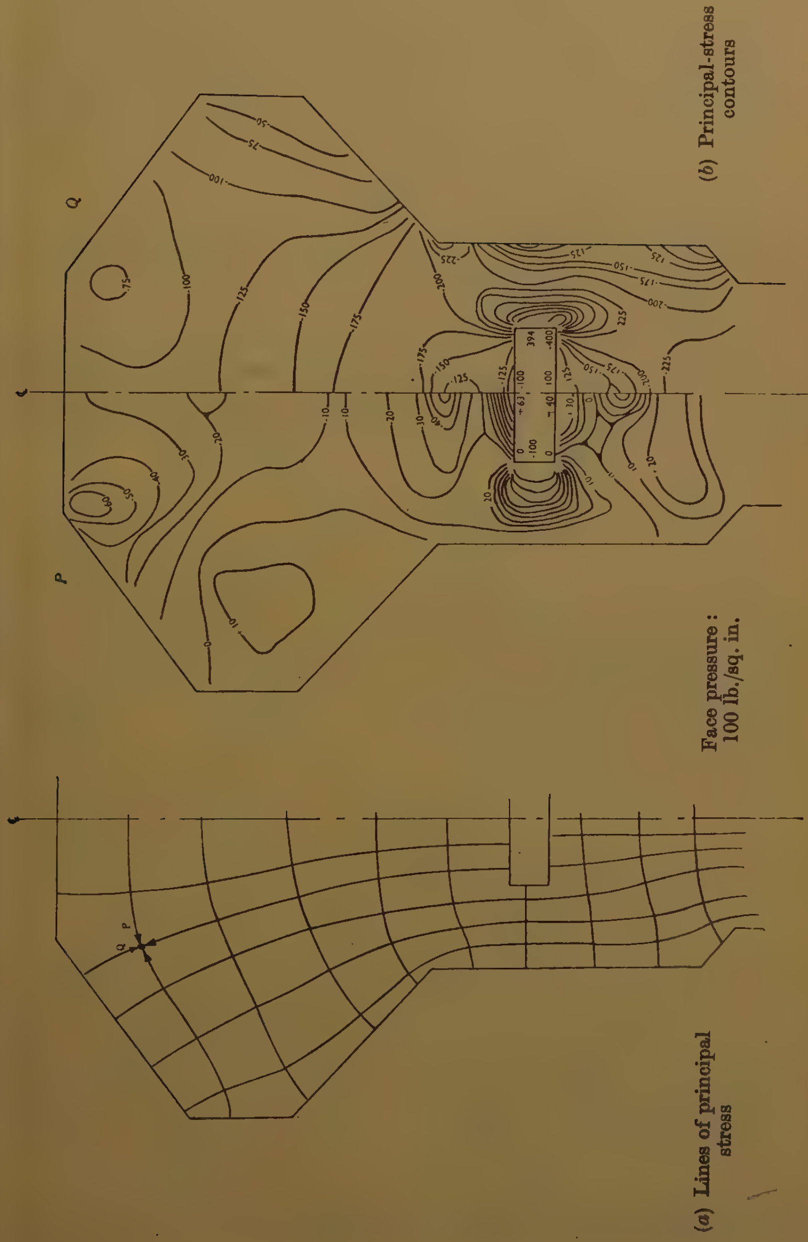
General Conclusions

The following conclusions were drawn from the work described in the Paper.

Method of Analysis

Agreement between calculated and experimental results is reasonable, and it is concluded that the method of calculation will give a reliable

Figs 24



PRINCIPAL STRESSES IN BUTTRESS HEAD WITH RECTANGULAR GATE SHAFT (SECTION "D")

estimate of the primary stresses in the buttress web of an actual dam of the shape investigated. It is obvious, however, that the ideal conditions assumed in the calculations are difficult to obtain in practice, even in a laboratory experiment; thus due allowance will have to be made in design for such contingencies as shrinkage, unknown base conditions, and the like.

Stress Distribution in the Diamond Head

The maximum stresses in the head of the dam are those arising from hydrostatic pressure; those resulting from gravity are comparatively small. The head is not so highly stressed as the buttress web and no dangerous stresses were observed.

The experiments confirmed that a circular hole could safely be made through the head and that a comparatively large gate-shaft could be formed in it without substantially increasing the stresses. In both cases, however, the need was evident for careful detailing and reinforcement to deal with local stress concentrations around these holes.

Acknowledgements

The Author wishes to express his indebtedness to the North of Scotland Hydro-Electric Board and Sir Alexander Gibb and Partners (at whose request the investigation described was carried out) for their permission to publish the results contained in this Paper. The work was carried out at King's College, University of London; thanks are due to the College authorities for provision of laboratory facilities. The author was very ably assisted in carrying out the work by Mr J. K. Tattersall, B.A., of the staff of Sir Alexander Gibb and Partners.

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The Paper is accompanied by four photographs and twenty sheets of drawings, from which the half-tone plates and the Figures in the text have been prepared.

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DEATHS

It is with deep regret that intimation of the following deaths has been received.

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Laurence Bendelow (E. 1927, T. 1950).
Sukhendra Nath Ghose, B.Sc. (E. 1920, T. 1926).
Martin Gimson (E. 1910, T. 1928).
Frank Harold Greenhough, B.A. (E. 1928, T. 1939).
John Black Morrison Hay, M.C., M.Sc. (E. 1924, T. 1936).
Alexander Burns Lawson, B.Sc.(Eng.) (E. 1917, T. 1929).
Henry Bridges Molesworth (E. 1889).

Associate Members

Ignatius Bulfin, B.A. (E. 1896).
John Ellis (E. 1910).
John Owen Jones (E. 1924).
Alexander Allen McClelland (E. 1918).
John Robertson (E. 1919).
Henry Thomas White (E. 1894).

OBITUARY

Colonel GEORGE ERIC HOWORTH, O.B.E., M.C., B.Sc., who died at Cults, Aberdeenshire, on the 11th January, 1954, was born on the 13th April, 1889. He was educated at Leys School, Cambridge, and at Manchester University. He began his career as Contractor's Engineer on construction of the Immingham Dock and London Dock prior to the 1914–18 war in which he served in the Royal Engineers. He was awarded the Military Cross and was mentioned in dispatches four times.

From 1919 to 1929 he was Resident Engineer on harbour construction work in the Island of Harris and at Zanzibar. For his work at Zanzibar he was awarded The Order of The Brilliant Star of Zanzibar. In 1930 he undertook the site investigation for the Lower Zambesi Bridge in preparation for tender, and until 1935 was Contractor's Agent for the construction of the bridge, which is one of the longest railway bridges in the world. From 1936 to 1942 he was Contractor's Agent for the New Howrah Bridge, Calcutta, the longest single span in Asia.

In 1942 he was selected for a senior post at the War Office. It was typical of him that he accepted this appointment only on the clear understanding that he would be permitted to go over to France with the invasion forces on " D " Day, which in fact he did.

While at the War Office, Colonel Howorth devised the methods later to be employed in the rapid repair and construction of port installations. He landed in Normandy as Deputy Director of Transportation, 21st Army Group, and was responsible until the end of hostilities for the construction and repair of ports in France, Belgium, Holland and Germany. In this work he was a constant source of inspiration to the officers who served under him.

From the end of the 1939–45 war until 1950 he was with Balfour, Beatty & Co., and was placed in charge of all their civil engineering undertakings in East Africa. From 1950 until shortly before his death, he was in private practice in Nairobi.

Colonel Howorth was elected an Associate Member in 1915, and was transferred to the class of Member in 1926.

He was the Author of two Papers presented to the Institution, the first on " The Construction of the Lower Zambesi Bridge," [1] and the second, in collaboration with Mr H. Shirley Smith, on " The New Howrah Bridge, Calcutta," [2] for which he was awarded a Telford Premium and a Coopers Hill Medal, respectively, by the Council of the Institution.

He is survived by his wife and two sons.

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[1] J. Instn Civ. Engrs, Vol. IV, p. 369 (Jan. 1937).
[2] J. Instn Civ. Engrs, Vol. XXVIII, p. 211 (May 1947).

GEORGE MATTHEWS HUTTON, who died at Dundee, Scotland, on the 2nd January, 1954, was born at Invergowrie, Perthshire, on the 28th January, 1891.

He received his early education at Harris Academy, Dundee, and later attended the Dundee Technical College where he became Armitstead Medallist.

In 1908, he commenced his training in the City Engineer's Department, Dundee. He subsequently became Deputy City Engineer to the Corporation of Dundee (1936), and from 1950, City Engineer, a position he held to the time of his death.

In 1914 he enlisted in the Scottish Horse in which he served until 1917, when he transferred to the Royal Engineers and was subsequently commissioned. He served in Egypt, Gallipoli, Greece, and France during World War I.

During his service with Dundee Corporation, Mr Hutton was responsible for the carrying out of several important main drainage schemes made necessary by the rapid expansion of the City and took a prominent part in the housing and industrial development of the area.

A number of important major road projects including 7 miles of the 160-foot-wide Kingsway By-pass were carried out under his direction.

Mr Hutton was elected an Associate Member in 1919, and was transferred to the class of Member in 1950. He was also a Member of Council of the Institution of Municipal Engineers, and a Member of the Dundee Institute of Engineers.

He is survived by his wife and by four sons and two daughters.

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